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# Combining the scenario technique with bibliometrics for technology foresight: The case of personalized medicine

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ABSTRACT

The purpose of this article is to present a novel method for combining bibliometrics and scenario technique for the sake of conducting technology foresight. First, we derive an eight-step scenario approach and add the identification of emerging technologies as well as their respective effects on each scenario. Second, we illustrate this combined method in the field of personalized medicine (PM). Existing literature on method combination often focuses singular challenges and benefits associated with the scenario technique. In this paper, however, we integrate the results of a bibliometric analysis at each step of the scenario technique. Herein, we refer mainly to the co-citation analysis and bibliographic coupling network. Third, we describe the findings of our case study for every step of the application of the scenario technique. In doing so, we offer practical guidelines for applying this novel combined method in other contexts. The overall benefit of the method combination is the integration of scientifically based information that exceeds the knowledge bases of the scenario team and other experts. Most notably, the examination of vast amounts of technology-specific information facilitates the identification of emerging technologies. Moreover, the combined method allows for a more precise projection of future states when narrowing the scenario funnel. Using this eight-step scenario approach, we build three scenarios for the field of PM, discuss disruptive events, and identify and integrate emerging technologies into each scenario. Finally, we explore strategic decisions for various stakeholders in the PM field.


## 1. Introduction

Technology foresight relates to the generation of accurate assumptions regarding the emergence of various technologies to inform strategic management decisions (Rohrbeck, 2011; Reger, 2001). Foresight experts within both academia and practice emphasize that available methods and tools should be combined to integrate expert knowledge with other valuable sources of information (Haegeman et al., 2013; Lüdeke, 2013; Popper, 2008; Malanowski and Zweck, 2007). Similarly, authors stress the importance of combining qualitative and quantitative methods (Haegeman et al., 2013; Lüdeke, 2013). However, the integration of quantitative, technology-specific information represents a significant challenge, particularly with respect to technology foresight. The most prominent qualitative technique that has been proposed for a method combination is scenario technique – a prominent and versatile tool designed to assist strategic management in coping with an unknown future (Ringland, 2010; Marcus, 2009). In the literature and in practice, the construction of scenarios is a systematic method for depicting a number of comprehensive pictures of possible futures (Ringland, 2010; Marcus, 2009; Schoemaker, 1995). Scenarios do not represent definite future states, but visions generated in a structured and creative process based on assumptions about what could happen (Schwartz, 1991; Wack, 1985). These assumptions are generated in a step-by-step

*Abbreviations:* PM, Personalized medicine; WoS, Web of Science; PESTEL, Political, economic, social, technological, ecological, and legal.

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procedure and are incorporated into strategy development (Mietzner and Reger, 2005). The inherent benefit of the scenario technique is its facility in coping with the range of possible futures, thereby opening up the horizon of participants and stakeholders to these futures and reducing their risk of making incorrect decisions (Schoemaker, 1995). Researchers have proposed a number of quantitative methods to optimize the accuracy of the scenario technique, including fuzzy clustering (Pishvaee et al., 2008), system dynamics (Piirainen et al., 2010), and diffusion models like the Fisher-Pry model (Daim et al., 2006).

In this paper, we emphasize the added value associated with combining methods and linking academia to practice. Specifically, we report a case study in the field of personalized medicine (PM) where we have used a combination of scenario technique and bibliometric methods to conduct technology foresight. In doing so, we contribute to existing scholarship on the method combination in three principal ways. First, we derive a scenario approach that is specifically focused on technology foresight; this approach is based on prominent approaches that have been described in the literature. Second, we demonstrate that the output creation in each step of the scenario technique can be complemented with bibliometric information. The combination of the scenario technique and bibliometrics represents a novel method within the field of technology foresight. The novelty of this approach fills a gap in a literature in which most scholars have focused on addressing single challenges in a single step of the scenario technique, e.g., a consistent clustering process (Pishvaee et al., 2008; Hirsch et al., 2013). Third, the description of our case study findings provides practitioners with guidelines for replicating our methodological approach. The applied nature of this paper extends current research about comprehensive methodologies, which has often remained conceptual in kind (Brose et al., 2013).

We have chosen to combine bibliometrics with scenario technique for multiple reasons. First, bibliometrics is a sophisticated and versatile technique that yields a variety of types of information, each of which is useful for integration at different steps of the scenario technique. Bibliometrics builds upon a large data basis of scientific articles. Applied to a specific field of technology its results include the intellectual structure, current research topics and publishing organizations, authors, and countries (Ma et al., 2014; Vogel and Güttel, 2013). Second, bibliometrics has long been used for forecasting using term frequency analysis (Woon et al., 2011) or bibliographic coupling (Huang and Chang, 2014; Kuusi and Meyer, 2007). Third, bibliometrics is useful for the analysis of only relatively short timeframes (Lichtenthaler, 2002) and scarcely captures the influence of socio-economic factors. However, when combined with the scenario technique, bibliometric information narrows the so-called scenario funnel by reducing the number of possible developments in the near future. As such, integrating bibliometrics results in more accurate long-term scenarios because the regular foresight timeframe of scenario technique is retained. The overall benefit of the combined method is the integration of broad, current and scientifically based information that exceeds the respective knowledge bases of both the scenario team and experts. Moreover, as will be demonstrated over the course of this paper, this combined method offers a holistic tool for technology foresight with a focus on identifying and evaluating emerging technologies.

The sections of this paper are organized as follows. In Section 2, we offer a short overview of the literature on method combination, with a particular emphasis on the research gaps identified above. In Section 3, we describe our eight-step scenario approach designed specifically for technology foresight. In addition, we outline challenges associated with each step in the technique, and emphasize the need to integrate quantitative information with it. In Section 4, we describe the applicability of bibliometric analysis and the types of information it can provide. In this section, we argue that the results borne from bibliometric analysis can complement every step of the scenario technique. To address our primary research goals, in Section 5, we describe how we integrated key results from bibliometric analysis into the scenario technique in the context of PM. We discuss in detail how bibliometrics has enriched output creation. Finally, in Section 6, we present our key findings and avenues for future research in this area.

## 2. Overview of literature on method combination

Several researchers and practitioners have suggested that combining methods can be a particularly effective foresight tool (Haegeman et al., 2013; Lüdeke, 2013; Popper, 2008; Malanowski and Zweck, 2007). To provide a comprehensive synopsis of various method combinations in the context of technology foresight, we used the Web of Science (WoS) database to perform a detailed literature review of relevant articles from the last ten years. This overview reveals that research has principally focused the combination of quantitative methods with either scenario technique or roadmapping (Table 1). The purpose was to improve single steps within these two underlying foresight tools. For example, researchers have combined the scenario technique with systems dynamics approaches to quantify the clustering process (Pishvaee et al., 2008; Hirsch et al., 2013). Bibliometric analysis has been used in combination with roadmapping or diffusion models to make qualitative assumptions more accurate by providing quantified information (e.g., performance measures of research efforts, identification of key experts in a research field). The inclusion of quantitative input into the whole scenario process, however, has not been researched to date. This highlights that our proposed method combination of bibliometrics and scenario technique is novel to the field of foresight. In the subsequent sections, we discuss the scenario technique and bibliometrics independently before describing the benefits associated with their combination in Section 5.

## 3. Scenario technique

### 3.1. The scenario technique as a key foresight tool

Within the field of strategic management, the scenario technique is considered a useful tool for long-term business planning (Bradfield et al., 2005). It enables the analysis of the current situation while systematically identifying areas of influence and accordingly deducing driving forces with their relationships (van der Heijden, 2000). A critical benefit associated with integrating scenario technique into strategic management is that it provides greater awareness of the factors that influence future events. In this way, scenario planning is "educational" [31, p.119], and has a substantial impact on strategic decision-making while opening the mindsets of all those that take part in it (Schoemaker, 1995; Coates, 2000). In the context of technology foresight, the scenario technique allows for the identification of emerging and disruptive technologies and related trends, as well as the envisioning of different technological futures (Saritas and Aylen, 2010). Recent examples in the literature demonstrate the myriad possibilities for applying the scenario technique including biomedicine (Niewohner et al., 2005), the water sector (Lienert et al., 2006), and wireless services (Ho and Chen, 2009; Pagani, 2009).

However, these examples have traditionally used different approaches when constructing scenarios. Moreover, none of them are designed to integrate quantitative technology-specific information, which is required for our case study. Therefore, in accordance with our first research goal, the following section compares prominent approaches in order to derive a scenario approach for conducting technology foresight in combination with a quantitative method.

### 3.2. Scenario approaches from literature

It is widely recognized that scenarios must be constructed and incorporated into strategy using a systematic step-by-step approach. Past researchers have proposed multiple approaches for conducting scenario technique (Mietzner and Reger, 2005). These approaches vary according to the different contexts, targets, and number of steps that comprise them. Mietzner (Mietzner and Reger, 2005) compared various scenario approaches, summarizing them in step-by-step concepts. The selected scenario experts and their main articles are Schwartz (Schwartz, 1991), von Reibnitz (Reibnitz, 1992), Heinecke (Heinecke and Schwager, 1995), Godet (Godet, 1987).

For the purposes of the current study, we refer to Mietzner's review and add the approaches of Gausemeier et al. (Gausemeier et al., 1998; Gausemeier et al., 2009), Schoemaker (Schoemaker, 1995) and Geschka (Geschka, 2006) in order to deduce an eight-step scenario approach specific to technology foresight. Table 2 summarizes the approaches that have been discussed in the literature, as well as the proposed eight-step approach.

Through a review of the various scenario approaches in the literature, we derived seven fundamental steps that are most common to these approaches (Table 2, excluding step 7). Given the degree to which they are omnipresent in the literature, these steps represent an aggregation of the common tasks used to create scenarios and transfer the results of scenario analyses to strategy. Within these fundamental steps, these approaches

**Table 1**
Overview of articles that combined bibliometric analysis or the scenario technique with other methods.

| Author | Title | Method combination | Description |
|---|---|---|---|
| Kostoff et al. (2004) | Disruptive technology roadmaps | Bibliometrics with roadmaps | Identification of core capabilities within an industry section and the description of their evolution |
| Drew (2006) | Building technology foresight: Using scenarios to embrace innovation | Scenario planning with technology roadmapping, expert analysis and creative group processes | Scenario technique as an integrative tool for analyzing disruptive innovation |
| Daim et al. (2006) | Forecasting emerging technologies: Use of bibliometrics and patent analysis | Bibliometrics with diffusion model (Fisher-Pry model) | Bibliometrics as a tool for identifying emerging technologies and as data input for the Fisher-Pry model |
| Pishvaee et al. (2008) | A fuzzy clustering-based method for scenario analysis in strategic planning: The case of an Asian pharmaceutical company | Scenario technique with fuzzy clustering | Quantification of scenario analysis; a method for building, analyzing, and ranking scenarios |
| Piirainen et al. (2010) | Translating scenarios for management: Use of system dynamics modelling to quantify scenarios | Scenario technique with system dynamics simulation | Quantification of scenario analysis regarding the clustering of projections and the identification of consistent bundles of alternatives |
| Saritas and Aylen (2010) | Using scenarios for roadmapping: The case of clean production | Scenario technique with technology roadmapping | Multiple futures thinking from scenario technique as an input for technology roadmapping |
| Hirsch et al. (2013) | Scenario planning with integrated quantification: Managing uncertainty in corporate strategy building | Scenario technique with system dynamics simulation | Quantification of scenario analysis regarding the clustering of projections and consistency analysis |
| Zhang et al. (2013) | A hybrid visualization model for technology roadmapping: Bibliometrics, qualitative methodology and empirical study | Bibliometrics with technology roadmapping | Construction of a hybrid model for composing technology roadmaps using visualization techniques and qualitative methodologies |
| Geum et al. (2014) | Combining technology roadmap and system dynamics simulation to support scenario-planning | Scenario technique with technology roadmapping and system dynamics simulation | Integrative approach to the technology roadmap; system dynamics for supporting scenario planning |
| Proposed approach | Combining the Scenario Technique with Bibliometrics for Technology Foresight: The Case of Personalized Medicine | Scenario technique with bibliometrics | Integrative approach that integrates key bibliometric analyses as input for each step of scenario technique for technology foresight |

**Table 2**
Comparison of scenario approaches and the proposed eight-step approach.

| Eight-step approach | Godet (1987) | Schwartz (1991) | Reibnitz (1992) | Schoemaker (1995) | Heinecke and Schwager (1995) | Geschka (2006) | Gausemeier et al. (1998, 2009) |
|---|---|---|---|---|---|---|---|
| 1. Define object of analysis | Construct the basis | Identify local issues | Analyze tasks regarding goals and strategies | Define the scope | Analyze initial problem | Define and structure the object of analysis | Assess the decision field |
| | | | | Identify the major stakeholders | | | Analyze scenario field |
| 2. Identify key driving forces and descriptors | Identify key variables | Identify key issues in the local environment | Identify key influence areas and factors | Identify basic trends | Identify influence areas and influence factors | Identify and structure key influence areas and driving forces | Derive key factors |
| | Identify major issues | List the driving forces | | Identify key uncertainties | | | |
| | | Rank the key factors and driving forces by importance and uncertainty | | | | | Reduce key factors using the system grid method |
| 3. Derive projections and decide on the number of scenarios to be built | Formulate key questions for the future | Select scenario logics | Derive projections and decide on the number of scenarios to be built | Construct initial scenario themes | Identify descriptors and projections | Derive descriptors and build projections and assumptions | Build bundles of alternatives and decide on the number of scenarios to be built |
| 4. Cluster projections into consistent bundles of alternatives | | | Cluster alternatives and check for consistency | Check for consistency and plausibility | Check bundles of alternatives for consistency | Build and select consistent bundles of assumptions | Check bundles of alternatives for consistency |
| 5. Describe scenarios | Elaborate explorative scenarios | Elaborate scenarios | Interpret scenario and visualize it | Develop learning scenarios | Interpret scenarios | Elaborate and interpret scenarios from the bundles of assumptions | Describe scenarios using retrieved information |
| | | | Derive consequences (opportunities, risks and actions) | Identify research needs | | | Select one reference scenario |
| 6. Identify disruptive events and their effects on the scenarios | | | Analyze disruptive events/ wild cards | | Analyze disruptive factors/wild cards | Analyze impact of disruptive events | |
| | | | | | | Refine the scenarios for the object of analysis and explore implications | |
| 7. Identify emerging technologies for each scenario | | | | | | | |
| 8. Explore the implications for strategy and derive plans for action | | Explore implication | Transfer scenario into strategy | Develop quantitative models | Analyze consequences | Derive plans for action | Check for risks and opportunities |
| | | Select leading indicators and signposts for strategy | | Evolve toward decision scenarios | Elaborate core strategy/scenario transfer | | Derive implications for strategy |
| | | | | | Link scenario technique with other methods/tools | | |

differ primarily with respect to the level of detail. For example, some authors emphasize the identification and selection of driving forces. This emphasis yields an additional step in the process designed to systematically reduce the list of driving forces. (Heinecke and Schwager, 1995; Gausemeier et al., 2009). Other researchers focus on clustering projections, thereby adding a step for conducting (quantitative-based) consistency analyses (Schoemaker, 1995; Niewohner et al., 2005; Burt et al., 2006). Von Reibnitz (Reibnitz, 1992) and Geschka (Geschka, 2006) included an analysis of unlikely (but potentially troublesome) future events to refine the scenarios in terms of dramatic, disruptive factors. Still others have delineated the scenario transfer step into several sub-steps when focusing the integration into strategic decision-making (Heinecke and Schwager, 1995; Gausemeier et al., 1998; Gausemeier et al., 2009).

### 3.3. Scenario approach for conducting technology foresight

Based on the steps derived from common scenario approaches, we included a step in which emerging technologies are identified and assessed in terms of their respective impacts on each scenario (Table 2, Step 7). We consider this addition to be crucial if the scenario analysis is meant for technology foresight purposes, especially when predicting the emergence of technologies and their evolution in different possible future states. Given its utility, we incorporate this step after the analysis of disruptive events and before the exploration of implications for strategy. In our experience, this yields optimal results for three reasons. First, the derived scenarios and disruptive events have already demonstrated the possibility of different futures to the scenario team and opened up its mindsets. This facilitates the identification of related future technologies. Second, the derived scenarios establish a clear future-oriented framework for predicting how emerging technologies could evolve. Third, this step must be integrated before implications for strategy are derived to support technology-related decision-making, e.g., technology-portfolio planning and make-or-buy decisions. Given the above, we derived the following eight-step approach (Table 2). It emphasizes the identification of emerging technologies (Step 7) as well as the transfer of findings into relevant technology strategy (Step 8):

1. Define object of analysis
2. Identify key driving forces and descriptors
3. Derive projections and decide on the number of scenarios to be built
4. Cluster projections into consistent bundles of alternatives
5. Describe scenarios
6. Identify disruptive events and their effects on the scenarios
7. Identify emerging technologies for each scenario
8. Explore the implications for technology strategy and derive plans for action.

### 3.4. Challenges associated with the scenario technique

In this section, we describe the eight-step approach in detail. While most existing proposals for combining methods highlight the use of quantitative methods to overcoming singular challenges associated with single steps in the scenario technique, we identify challenges for every step of the technique and discuss them in the context of technology foresight. This addresses our second research goal: to demonstrate how the whole scenario process can benefit from the integration of quantitative results. In the course of this paper, using a case study in the field of PM, we describe how bibliometrics helps to overcome the listed challenges.

#### 3.4.1. Define the object of analysis

Coates outlined the importance of understanding the object of analysis ("universe of concern" [31, p. 117]) as a fundamental step. Given this, referring to system thinking as a fundamental assumption for building scenarios, the first step in the process is to obtain a comprehensive picture of the object of analysis through some visualization method (e.g., illustrating the issue as an entity-relationship model (Gausemeier et al., 2009)). This visualization can help to support decisions related to (1) the appropriate number of entities in the entity-relationship model and (2) the appropriate amount of detail regarding description of those entities. To ensure comprehensiveness, the scenario team can apply the PESTEL model (Political, Economic, Sociological, Technological, Ecological, and Legal driving forces) (Burt et al., 2006; Walsh, 2005).

In the context of technology foresight, the scenario team must assure that the scope of the analysis provides sufficient opportunity to identify new challenges. If the scope is too narrow, the probability of identifying emerging technologies for each scenario drops significantly. If the scope is too broad, the scenario team may be imprecise in their projections.

#### 3.4.2. Identify key driving forces and descriptors

In the second step of the process, the scenario team identifies key driving forces and their descriptors. In general, the greatest challenge associated with this step is creating a comprehensive list of drivers that incorporates the judgments of all stakeholders. As with the first step, this step can be supported with a complementary qualitative method for analyzing the macro-environment (e.g., the PESTEL model (Burt et al., 2006; Walsh, 2005)). Key drivers must be internally consistent, externally heterogeneous (Battistella and de Toni, 2011), and fit the defined scope of the analysis. Moreover, well-known trends must be transformed into organization-specific descriptors (Battistella and de Toni, 2011). To optimize the results associated with this step, all internal and external technology-specific information should be leveraged to increase the scenario team's expert knowledge (Coates, 2000).

#### 3.4.3. Derive projections and decide on the number of scenarios to be built

Following the identification of the key driving forces, the scenario team projects possible future scenarios. This reflects the true visioning component of the scenario technique. The core activity associated with this step is the development of multiple futures for the key driving forces. Gausemeier et al. (Gausemeier et al., 1998) suggest building up to three possible developments for each driving force. In general, the appropriate number of projections is equal to the number of scenarios to be developed. Depending on the specific purpose of the scenario project, this can range from two to five scenarios (Amer et al., 2013). Of all possible variations, a three-scenario framework with two extreme scenarios and one trend scenario is the most commonly used (Gausemeier et al., 1998; Amer et al., 2013). The most important challenge of this step is the development of appropriate projections for each descriptor. Similar to the previous step, a scenario team's knowledge base can be enriched by integrating quantified technology-specific data to underpin alternative assumptions and avoid fantastic projections.

*3.4.4. Cluster projections into consistent bundles of alternatives*

In this step, the scenario team groups projections into separate bundles to create the first raw versions of the scenarios. Generally, the clusters of projections must be consistent, stable, and heterogeneous (Reibnitz, 1992; Schwab and von Reibnitz, 2000). Researchers have argued that in this step, more than others, quantitative methods can be applied, e.g., system-dynamic-based simulation (Piirainen et al., 2010; Hirsch et al., 2013), clustering algorithms for multivariate data (Gausemeier et al., 2009). Even if supported by clustering algorithms, the scenario team should perform a final check on the scenario bundles to ensure their validity and consistency. When engaging in technology foresight, alternative projections often reflect the rise and/or fall of emerging technologies. Evaluation of the consistency between these projections is challenging, as the interdependence of future technological developments is difficult to predict or assess.

*3.4.5. Describe scenarios*

In the most creative portion of the scenario technique, the scenario team fleshes out scenarios such that they become portraits of the future. This step aims to open the minds of the scenario team to prepare for scenario transfer (Schoemaker, 1995; Shell International BV, 2008) and to create a document for internal and/or external communication. There are no set rules on how to construct good scenarios, but some authors have suggested guidelines. For example, van der Heijden (van der Heijden, 1997), as summarized by Chermack (Chermack, 2005), asserted that well-written scenarios are (1) "internally consistent and plausible," (2) "link historical and present events with hypothetical events in the future," (3) "carry storylines that can be expressed in simple diagrams," and (4) "identify signposts or indicators that a given story is occurring" [49, p. 61]. In the context of technology foresight, this step can pose a unique challenge as the mindsets and imaginations of technology experts are often rich in detail but selective in attention (Wack, 1985). As a result, these experts often adhere to technology-centric points of view by neglecting other perspectives, including those driven by market trends or business models.

*3.4.6. Identify disruptive events and their effects on the scenarios*

Disruptive events – also known as "black swan" events [50, p. xviii] – are future events with a low probability of occurrence but a high impact on other events and the environments in which they occur (Reibnitz, 1992; Taleb, 2007). Famous examples include the financial crises (Taleb, 2007) or the oil shocks in the 1970s (Wack, 1985; Shell International BV, 2008). In addition to these large-scale disruptive events, Taleb (Taleb, 2007) argued that individual companies must also contend with events that pose unique threats to their respective strategies. In the context of technology foresight, companies must identify weak signals that could grow to become highly disruptive events. It is important to note that although the emergence of a new technology may be disruptive in nature, it should not be confused with a "disruptive event". Whereas the former involves deliberate development over time, the latter occur abruptly and unexpectedly.

*3.4.7. Identify emerging technologies for each scenario*

In general, the scenario team transfers results from the scenario analysis to strategic management (Steps 7-8) after describing the scenarios and identifying disruptive events. Depending on the motivation for conducting technology foresight, researchers have suggested a variety of methods, tools, and processes to glean strategy-related information from the scenarios (Reibnitz, 1992; Gausemeier et al., 2009). For technology-intensive companies, the purpose is the identification of emerging technologies, as they can alter the foundations of the companies' well-established business models. Therefore, in the context of technology foresight, it is critical to include a separate step to identify emerging technologies (Fink et al., 2004). Especially, analyzing these technologies on a concrete level is very challenging. This step is critical for technology-based companies not only to identify signals of impending technology-related disruptive events, but also to promote their own technological innovations to cultivate a diverse technology portfolio.

*3.4.8. Explore the implications for technology strategy and derive plans for action*

In the context of technology foresight, an important task for managers are make-or-buy-decisions. As a result, they must also make decisions about the allocation of the R&D budget, especially regarding new development strategies (e.g., new fabrication sites, new business partners). These decisions are difficult in light of emerging technologies and few available experts inside the company to determine the impact of their emergence. Given the above, it is imperative for companies to identify partners or experts in the respective research fields to integrate them into future decision-making.

To summarize, the challenges associated with each step of scenario technique highlight the need to integrate quantitative methods as a means of providing additional and critical information. However, leveraging different quantitative methods for each step requires methodical expertise of the entire scenario team. Even foresight experts can struggle when a variety of methods are combined (Prajogo and Ahmed, 2007). Therefore, we propose the use of a novel method combination: bibliometrics and scenario technique. Bibliometrics - a powerful and sophisticated method - yields input during application of all steps in the scenario technique, thereby addressing all challenges listed in this section. In the following section, we provide a brief synopsis of bibliometrics, its core methodology, and key results. Following this, we describe how bibliometrics can be combined with the scenario technique in Section 5.

## 4. Bibliometric analysis

*4.1. Definition and scientific roots*

Coined by Pritchard (Pritchard, 1969), the term "bibliometrics" was originally intended to replace the term "statistical bibliography." Generally speaking, bibliometrics involves the application of mathematical and statistical methods on literature that is not necessarily scientific in kind (de Bellis, 2009; Hood and Wilson, 2001; Pritchard, 1969). However, scientific databases are most commonly analyzed. Even when focused specifically on technology foresight, the results of a bibliometric analysis have several applications (Havemann, 2009; Moed, 2005). Most important of these is the application of bibliometrics to (1) identify future developments of specific scientific fields (Woon et al., 2011; Huang and Chang, 2014; Shibata et al., 2011), (2) structure a research field in terms of key authors or countries (Sakata et al., 2013; Di Stefano et al., 2012; Ponzi, 2002), or (3) detect contextual factors, like forms of cooperation or funding types (Abramo et al., 2012; Matthiessen et al., 2010; Butcher and Jeffrey, 2005).

By promoting the use of bibliometrics in conjunction with mathematical graphs to facilitate more nuanced analyses, Price (Price, 1965) provided an important contribution to the success of the former (Radicchi et al., 2012; Schiebel, 2012). These graphs are called networks in bibliometrics and are comprised of nodes (e.g., authors, journal articles) and edges that depict pairwise connections between the nodes. When nodes are defined as individual articles, the pairwise connections between them (i.e., the edges) represent bibliographic coupling or co-citation (Schiebel, 2012; Boyack and Klavans, 2010; Marshakova-Shaikevich, 1973; Small, 1973; Kessler, 1963). If authors are the object of analysis, however, the edges represent co-authorship (Havemann, 2009).

### 4.2. Bibliometric networks

Two articles are bibliographically coupled if they reference the same third article. Couplings between nodes are stronger if they co-cite multiple articles. In contrast, two references are connected by co-citation if they are both referenced in a third article. Both measures are based on the assumption that cited and citing articles hint at similarity in terms of thematic content. Because an article must be published before it can be cited, clusters of co-cited papers are called knowledge bases, and papers coupled bibliographically represent research fronts of the latest publications (Persson, 1994).

The emergence of different software tools has assisted the well-established field of bibliometrics to gain prominence in a variety of scientific areas. The most notable advantage of these software tools is the visualization of bibliometric networks to identify research fronts and knowledge bases in a large amount of articles. Depending on the used bibliometric software, the visualization techniques differ greatly (Cobo et al., 2011). For the purposes of this paper, we derive the networks with BibTechMon™. BibTechMon™ was developed by the Austrian Institute of Technology, and uses a visualization algorithm based on the Kopsca's (Kopcsa and Schiebel, 1998) spring model. Moreover, the software provides a spatial density map for better cluster identification (Schiebel, 2012). In the following paragraph, the underlying principles of the spring model are explained, whereas a detailed description of the density map can be found in Schiebel (Schiebel, 2012).

In the visualization procedure, each node (representing an author, publishing organization, or article) is randomly distributed in a two-dimensional space. The nodes are simulated as equally charged particles, which leads to a resulting repulsive force (Kopcsa and Schiebel, 1998). If two nodes are connected by bibliographic coupling or co-citation, they are joined by a spring, which represents an attracting force. The constant associated with the spring represents the strength of the connection between the nodes that it joins (Chen, 1999). The resulting forces are then iteratively calculated for every node and they are moved in the direction in which the forces are driving them (Golbeck and Mutton, 2006). The algorithm continues until a preset amount of iterations is executed or the resulting node movement lies below a given limit. The final result consists of networks comprised of clusters of papers grouped according to their content and thematic proximity. The clusters (see Section 5 for examples) can then be analyzed in detail in BibTechMon™. The articles in the clusters can be selected and the metadata related to the articles can be displayed (i.e., title, abstract, publication year). In evaluating this information, every cluster can be tagged in terms of the common theme.

### 4.3. Key results of bibliometric analysis

The evaluation of metadata available in scientific databases and the mapping of bibliometric networks yield a number of valuable results. These results include:

- Knowledge bases: Identified in the co-citation network, knowledge bases represent the scientific roots of a research field.
- Research fronts: Represented as clusters in the bibliographically coupled network, they indicate the directions of current research within the scientific field under investigation.
- Research portfolio: The portfolio illustrates the development and relative importance of the clusters in the networks. Presented in the style of a BCG-Matrix, the research portfolio depicts research fronts according to their relative share of total publications on the x-axis and the growth rate on the y-axis.
- Core articles: Using centrality measures based on citations, it is possible to identify significant papers in each research front or knowledge base. They represent important contributions to research, critical turning points, or review papers.
- Term frequency analysis: This allows for easier identification of terms. The analysis can be performed to focus on keywords, titles, abstracts, or (if available) full text.
- Networks of authors or organizations: Based on co-authorship, these networks visualize the proximity of authors or organizations, and thereby illustrate their cooperation.
- Main authors, organizations, and countries: The number of times each author, organization, or country is cited in the population of studies -or in a given cluster- can be counted.

It is advisable to counter-check and compare these results to produce additional information, e.g., the convergence of research fields, the development of a research field over time.

### 4.4. Limitations of bibliometric analysis

Although bibliometrics is a powerful approach and gaining in popularity among researchers and analysts, it is subject to various limitations. Some of these limitations are related to bibliometric analysis in general; others relate to its use in the context of technology foresight. First, all bibliometric analyses are based on the assumption that the research field's relevant knowledge is in print within academic sources (Ávila-Robinson and Miyazaki, 2013; Shibata et al., 2008). However, the knowledge that can be found in academic journals represents only a portion of that which can also be found in patents, expert opinions, or all other non-academic sources. Some knowledge is altogether inaccessible, e.g., due to non-disclosure agreements. Second, publications relevant to the theme under investigation must be properly identified through an accurate choice and configuration of query terms (Woon et al., 2011; Sakata et al., 2013). Third, a complex citing behavior (e.g., self-citation, or completeness of literature-reviews) can result in citations that are not content-specific (Bornmann and Daniel, 2008).

In the context of technology foresight, qualitative analysis is often needed to perform an in-depth evaluation of contextual factors, e.g, public funding, or market needs (Hanisch and Wald, 2012; Niu, 2014). To identify emerging technologies, this need is underpinned by the fact that scientific success does not necessarily lead to market success or innovation breakthroughs. Finally, bibliometrics are sensitive to time, both in terms of the rather short foresight timeframes to which they may be applied (Lichtenthaler, 2002) and the time lag associated with bibliometric measures. It takes up to two years for completed research to be published, and perhaps another two years for that research to be cited (Shibata et al., 2008). Taken together, these shortcomings indicate that for bibliometrics to be a valuable tool for technology foresight it must be complemented with qualitative methods (such as the scenario technique).

## 5. Combining bibliometrics and scenario technique

In the previous sections, we explained the nature of the scenario technique and bibliometrics, as well as the potential benefits of integrating quantitative and qualitative methods. In this section, we illustrate a specific method involving the aforementioned methodologies. Because they redress each other's shortcomings, the combination of these two methods results in a holistic tool useful for conducting technology foresight. The integration with scenario technique allows for long term projections and consideration of socio-economic factors, thereby overcoming the short timeframe associated with bibliometrics. Similarly, bibliometric approaches are useful for the assessment of near-term technological developments, thereby avoiding unrealistic assumptions and narrowing the scenario funnel within the scenario technique. Hence, the combined method allows for the accurate analysis of long-term scenarios. In addition, key results from bibliometric analyses facilitate the identification of emergent technologies. The overall benefit of the method combination is the tool-supported integration of broad, current information from scientific literature that exceeds the scenario team's knowledge base.

The following sections depict a case study from the field of PM. This case illustration demonstrates how bibliometric analyses complement the output produced by the scenario technique at each step. In illustrating the use of this combined method, we address our second and third research goal. We provide a guide with which practitioners can perform technology foresight applying the proposed method combination.

For this study, the team consisted of the authors of this paper (as experts in methods) and content-specific experts. The latter experts come from different institutions or companies and possess substantial knowledge related to biotechnology, pharmacy, and medicine. The team members' goals were to (1) produce a comprehensive picture of future possible states of the field of PM, (2) identify emerging technologies in this field, (3) assess the future roles of these technologies in the different future states, and (4) describe their implications on strategic decision-making. Through moderated interviews and workshops, the methods experts trained the scenario team in the eight-step approach described in Section 3 (see Table 2). As data, we used the scenario team's inherent expert knowledge and the information gleaned from bibliometric analyses of scientific articles drawn from the WoS.

Fig. 1 provides a brief illustration of how the results of the bibliometric analysis were incorporated into scenario technique.

### 5.1. Object of analysis

The purpose of the first step in the eight-step approach was to disaggregate the major elements of the PM construct and identify the associations between them (Gausemeier et al., 2009). The understanding of PM in scientific literature can be defined in either a narrow or broader way. Articles from the researchers with a narrow perspective define PM as the sum of technologies for diagnostics and the specific development of therapeutics based on the analysis of genetics or molecular medicine (Offit, 2011). A broader definition includes the preventive identification of the risks of diseases and the observation of the course of the disease to support flexible, dynamic therapy adjustments (Abrahams, 2009). Here, we adhere to the broader perspective. Given this, we focus on how PM research and practice in Europe will develop in the next 15 to 20 years. To evaluate this, the scenario team constructed an entity-relationship model related to PM with entities and their relationships. The entities represent key stakeholders (e.g., patients, hospitals, research laboratories, pharmaceutical companies, regulatory authorities, health insurance companies) and trends (e.g., individualization, demographic development, genome-based technologies, information and communication technology). The steps we took to construct the entity-relationship model using WoS data and the co-citation network are summarized as follows.

First, we created a data set from the WoS (Core Collection, 2008-2014) performing a topic search using the terms "personalized medicine" and "diagno*". We derived these search terms iteratively to reduce the number of search hits to a manageable, but representative data set. In April of 2014, this search strategy generated a corpus of 953 publications. Second, to obtain an understanding of the topics intrinsic to these papers, we evaluated the WoS categories. Moreover, to ensure the comprehensiveness of this analysis, we applied the PESTEL model (Burt et al., 2006; Walsh, 2005). According to the WoS, most articles were from the field of natural sciences. Additionally, a fair amount of articles came from the fields of economics and health cares. Other articles belong to the fields of law, ecology and political science. It was evident from this analysis that economic issues had to be included explicitly into the entity-relationship model,

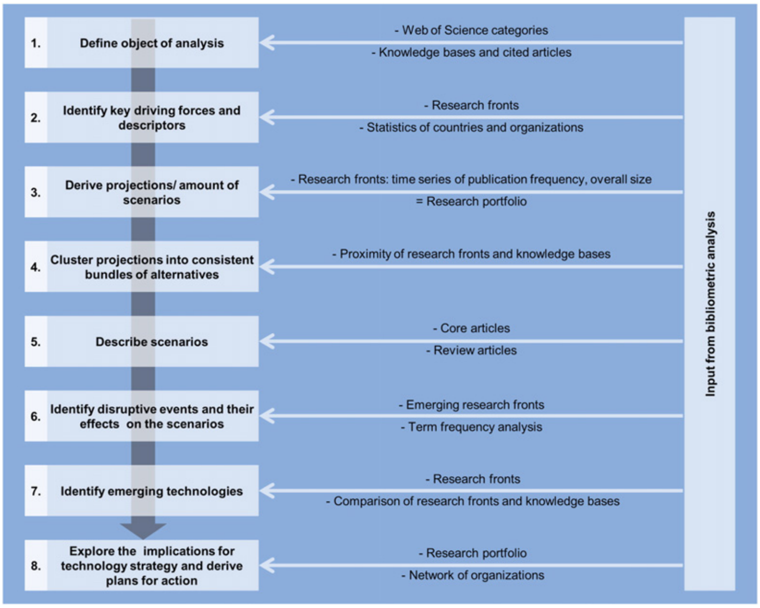


**Fig. 1.** Input from bibliometric analysis for each step in the scenario technique.

e.g., cost effectiveness, and funding sources. Third, we analyzed the knowledge bases as an indicator of the scientific knowledge used in the community of PM research. Fig. 2 illustrates the co-citation network graph, showing seven knowledge bases.

They include a variety of topics (see Table 3), e.g., technologies for DNA sequencing, nanomedicine, and regulatory and legal issues. Hence, topics beyond the natural sciences required integration into the entity-relationship model like privacy or reimbursement. This example illustrates that

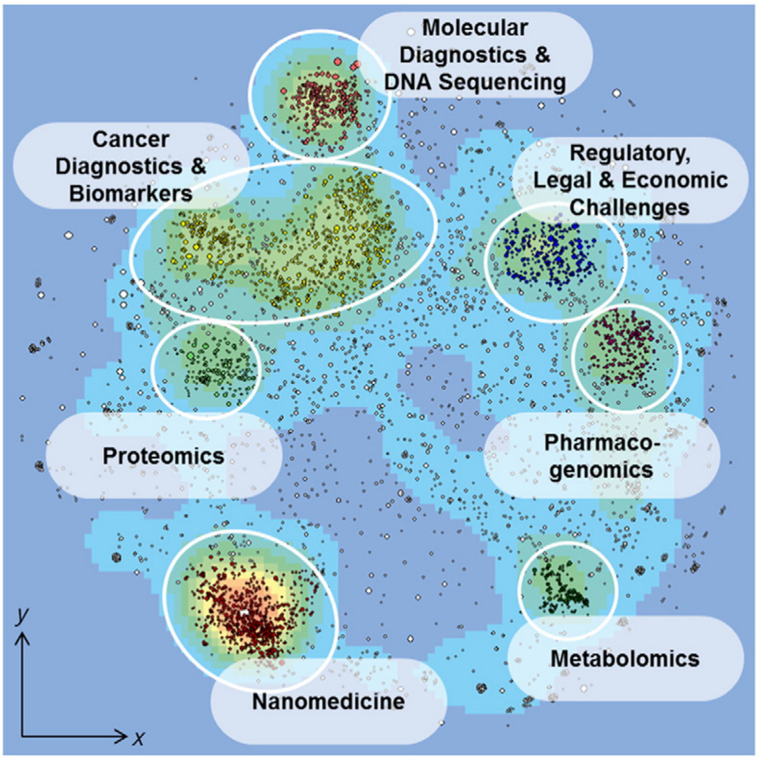


**Fig. 2.** Knowledge bases of personalized medicine represented by 6300 nodes and 292757 connections. Cited references of the extracted WoS data set as dots. Dot size indicates citation frequency. Local coordinates *x* and *y*. Local density of co-cited publications calculated with a cosine weighted moving average as background colors.

**Table 3**
Knowledge bases.

| Knowledge base | Description |
|---|---|
| Molecular Diagnostics & DNA Sequencing | Includes articles related to DNA sequencing technologies and molecular diagnostics as the key enabler to personalized medicine. Represents the scientific roots of next-generation sequencing technologies (e.g., MPSS or 2-base encoding). |
| Cancer Diagnostics & Biomarkers | Includes articles that depict the shift from organ-based categorization systems to the unique tumor concept. Contains the first steps towards more sophisticated cancer classifications with the help of different biomarkers. |
| Proteomics | Includes studies related to proteoms, entire sets of proteins. Primarily refers to protein profiling by mass spectroscopy, as proteoms can be used as biomarkers in personalized medicine. |
| Pharmacogenomics | Relates to studies concerning the interdependence of genetics and drug responses, as well as appropriate therapies and drug delivery systems. |
| Metabolomics | Includes studies focused on chemical processes and small molecules to characterize cell physiology and biochemical events. |
| Regulatory, Legal & Economic Challenges | Contains articles referring to study designs during approval processes, protection of research findings, cost-effectiveness, or reimbursement. |
| Nanomedicine | Includes studies concerning the first applications of nanotechnology in personalized medicine. Relates to diagnostics with a focus on imaging and drug-delivery options. |

evaluating the knowledge bases can help to overcome challenges associated with defining the appropriate scope of the scenario analysis and identifying all relevant areas of influence.

### *5.2. Identify key driving forces and descriptors*

After defining the object of analysis, the scenario team brainstormed (Schwartz, 1991) and used the PESTEL model (Burt et al., 2006; Walsh, 2005) to identify a set of driving forces. Some authors have suggested integrating information from bibliographic network to refine technology-related drivers (Kuusi and Meyer, 2007; Boyack and Klavans, 2010; Shibata et al., 2009). In this section, we demonstrate on an exemplary level how bibliometrics complements the detection of key forces by facilitating the identification of drivers from research fronts and descriptive statistics of the underlying literature data set.

Fig. 3 provides a three-dimensional visualization of the various research fronts that comprise the current state of the field of PM. This density map is an alternative visual representation of a network where edges constitutes bibliographic coupling (Schiebel, 2012). This is similar to the co-citation network depicted in Fig. 2 (Section 4). The depicted surface represents the local density of articles in the network, which better visualizes cluster size (height of the peaks) and cluster similarity (proximity of the mountains) than the more traditional network illustration.

Fig. 3 demonstrates that the research fronts are dominated by technologies concerning diagnostics and cancers. In addition, a large number of articles relate to challenges associated with translating research into clinical practice.

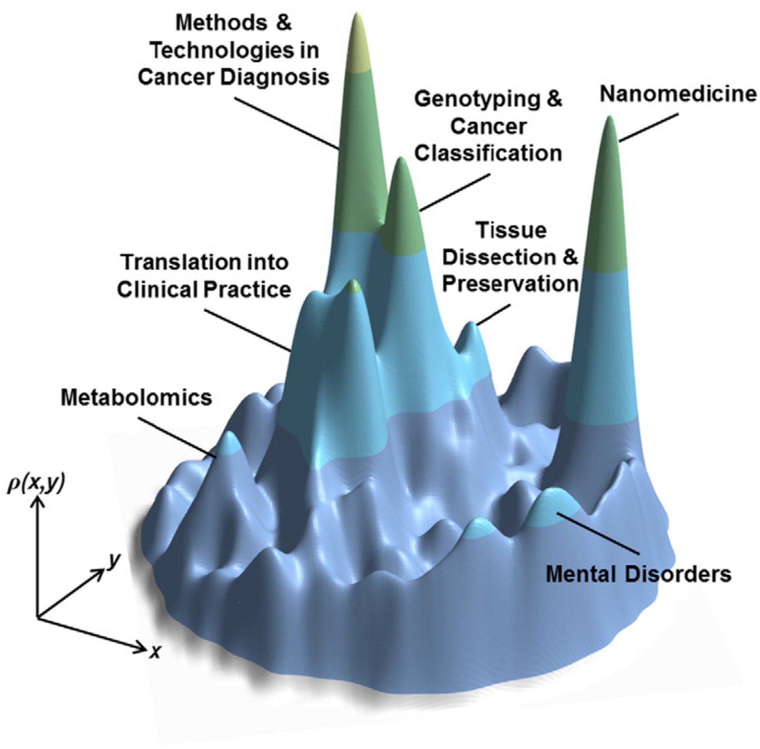


**Fig. 3.** Research fronts of personalized medicine in three-dimensional space. Local coordinates $x$ and $y$. Local density $\rho(x,y)$ of bibliographic coupled publications calculated with a cosine weighted moving average.

**Table 4**
Research fronts.

| Research front | Description |
|---|---|
| Methods & Technologies in Cancer Diagnostics | Contains articles from the fields of genome-sequencing, mass spectroscopy, and accurate biomarkers. Papers focus standardized study design, proper documentation of methods and results for further usage, and possible technological advances. |
| Genotyping & Cancer Classification | Contains articles concerning the application of aforementioned methods and technologies on the various cancer and disease types. Geared towards compiling a detailed categorization system for appropriate therapies and drugs. |
| Tissue Dissection & Preservation | Comprised of studies on tissue dissection and preservation that is basic for most diagnostic methods. Focuses primarily on the acquisition, dissection, isolation, and preservation of tissue, cells, proteins, or molecules to be analyzed. |
| Translation into Clinical Practice | Includes studies concerning the translation of personalized medicine into practice. Studies address cost-effectiveness, reimbursement policies, resident training, and implications for health care systems. |
| Metabolomics | Contains articles related to metabolomics in general. Focuses on the study of chemical processes and small molecules to characterize cell physiology and biochemical events. |
| Mental Disorders | Contains research regarding mental disorders, their connection to different "omics" technologies and the appropriate therapeutic strategy. |
| Nanomedicine | Contains research related to the application of nanotechnology to the field of personalized medicine. Studies relate to diagnostics, with a focus on imaging and options for drug-delivery. |

Finally, one upcoming research front concerns mental disorders. Table 4 summarizes and describes the research fronts. Two of them are similar to the knowledge bases (Metabolomics and Nanomedicine) and represent the continuation of the respective research.

To identify key drivers, the scenario team looked deeper into every cluster. For example, the "Genotyping & Cancer Classification" cluster highlights the importance of databases and the availability of genomic data. Given this, we integrated "Big data" or "ICT" into our construction of the scenarios. We derived another driver from the research front labeled "Translation into Clinical Practice." For this research front, the key topic (in addition to regulatory issues) is the education of physicians, pathologists, and residents as a means to accelerate the comprehensive diffusion of personalized medicine.

In addition to analyzing the research fronts, we also evaluated the number of organizations and countries from which the articles originated. Unsurprisingly, most articles were produced by authors at universities. Although non-university organizations may choose not to publish their research to avoid disclosing sensitive data to the public, the marked lack of firms among the authors of the research indicates that the PM field is currently at the increasing portion of the prevalent technology s-curve (Tseng and Tsay, 2013). Because many research activities occur within the public domain, "Public Funding" and the "Adaptation of the Health Care Systems" emerge as highly relevant drivers of the future of PM.

Furthermore, nearly all research is conducted in developed countries. This finding supports the assumption that PM is primarily geared toward markets in developed countries because the costs for the diagnostics procedures are still rather high even though they have decreased dramatically in the last years (Moch et al., 2012; Faulkner et al., 2012; Gurwitz et al., 2009).

In sum, integrating the information from the bibliometric analysis into the scenario team's brainstorming allowed for the identification of a more complete set of drivers and their associated descriptors (Table 5). This result illustrates that bibliometrics supports productivity in the second step of the scenario technique. To further illustrate the combined method, we selected a small excerpt of the compiled driver list (Table 5) to be used in the subsequent steps.

**Table 5**
Examples of key driving forces with descriptors of personalized medicine.

| Key driving force | Descriptors |
|---|---|
| Diffusion into Other Disease Categories | • Published Articles in Regard to Mental Disorders or Infectious Diseases<br>• Public Funding of Research Activities in PM |
| Translation into Clinical Practice | • Number of Residents with Education in PM<br>• Access to Genomic Data in Specific Databases |

### *5.3. Derive projections and decide on the number of scenarios*

In this step of visioning, the scenario team produced alternative projections for the descriptors of the key driving forces. To enrich this creative process, we relied primarily on the density of bibliographically coupled publications (Fig. 3) and its translation into the research portfolio (Fig. 4) that depicts the dynamic evolution of the research fronts outlined in the previous step. This helps to determine the starting points of the projections and to provide evidence for their development in the near future.

The research portfolio shows that although "Methods & Technologies in Cancer Diagnosis" is still a prominent research front, "Translation into Clinical Practice" is also quite important, thereby illustrating the efforts of some researchers to promote the realization of PM in practice. The proximity of "Metabolomics" or "Nanomedicine" to these top research fronts suggests a possible convergence of the fields in the near future. In addition, articles related to "Mental Disorders" represent a fairly new front with a moderate growth rate. The relative novelty of the "Mental Disorders" research front is also apparent in the bibliographically coupled network in which the field of "Mental Disorders" has virtually no edges connecting it to other research fronts. Owing to its novelty, this lack of connections indicates that it is unlikely for "Mental Disorders" to converge with other research fronts in the near future.

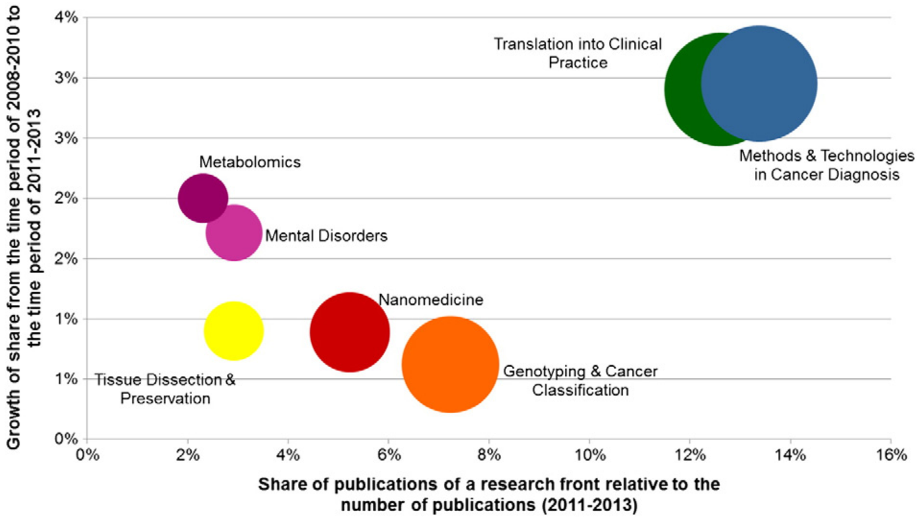


**Fig. 4.** Research portfolio of personalized medicine. Dot size indicates number of publications (2008–13).

To illustrate the process of developing projections, we refer to two key driving forces and focus on one descriptor for each (Fig. 5).

We made three alternative projections with respect to the descriptor called "Public Funding of Research Activities in PM" that belongs to the driver "Diffusion into Other Disease Categories". These projections are (1) a steady growth starting in a few years, (2) an s-curve development, and (3) a remaining constant level. Because the knowledge base associated with regulatory issues has fully converged into the cancer treatment research front, policymakers are likely to remain focused on cancers in the near future. Shifts towards other diseases will take time. Given this, for projections (1) and (2) we assumed that there would be an increase in public funding in the coming years. We further assume that the s-curve will emerge in response to an increase in private investors entering the market. For this projection, the private investors will ultimately serve as a substitute for public funding in the long run. Finally, we projected a third possibility in which high regulatory barriers would preclude any public funding.

The research portfolio suggests that the "Number of Residents with Education in PM" descriptor, measuring the "Translation into Clinical Practice" driver, initially begins at a low level, but is characterized by high growth rates in the future. Given this, it would not be plausible to predict a decrease. Nevertheless, following the "what might happen perspective", that is needed for the scenario technique, we assumed (1) continuing growth and (2) exponential growth and (3) a leveling off. As for both the shown examples as well as for most other descriptors three alternative projections were

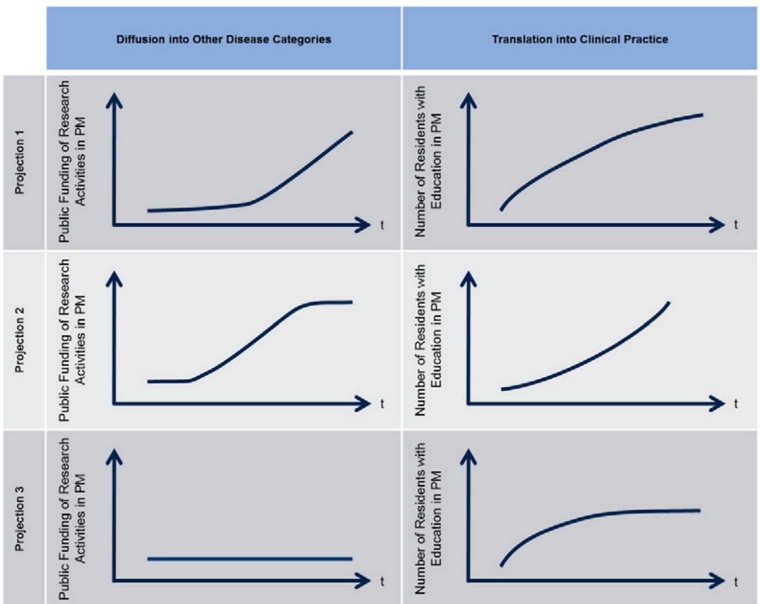


**Fig. 5.** Excerpt of the key drivers of personalized medicine with descriptors and assumed qualitative projections.

**Table 6**
Input from bibliometric analysis into Scenario 1.

| Main components of scenario | Article | Research field | Information from article |
|---|---|---|---|
| (1) Scarce public funding | (Offit, 2011) | Genomic testing | Lack of reimbursement: "Commercial genomic testing labs, as well as genomics-based pharmaceutical companies will require this evidentiary foundation to obtain reimbursement for medical services" (Offit, 2011, p. 11). |
| (2) Poor education of practitioners in personalized medicine | Katsanis and Katsanis (2013) | Molecular genetic testing | Personalized medicine is restricted to some areas of the world (p. 417). |
| | McCarthy et al. (2013) | Genomic medicine | Lack of adequate education of healthcare providers (p. 11). |
| (3) Lack of studies on cost-effectiveness | Tonellato et al. (2011) | Next-generation sequencing (NGS)/whole-genome analysis (WGA) | Adequate reimbursement is needed: "Pathologists must take the lead in proving that genome-based clinical laboratory testing can be cost-effective by truly optimizing evidence-based precision diagnostics and thereby reducing the propensity for mistakes" (Tonellato et al., 2011, p. 1). |
| | Moch et al. (2012) | NGS/WGA for molecular tumor profiling | "Only when well-designed clinical studies convincingly demonstrate the predictive value of NGS- or WGA-based tests, will the implementation of such molecular tumor profiling become accepted and integrated in diagnosis and treatment of cancer" (Moch et al., 2012, p. 5). |
| (4) Lack of studies on risks and benefits | Chin et al. (2011) | Cancer genomics | Assessment of risk and opportunities requires substantial evidence, which is why PM is palpable in research, but not in clinical practice (p. 302). |
| (5) Lack of regulatory framework dealing with property rights | Katsanis and Katsanis (2013) | Molecular genetic testing | Privacy discrimination: Genomic data can be used to identify patients in life and health insurance (p. 422). Genomic data can be hacked; cyber-security issues need to be addressed. |
| | McCarthy et al. (2013) | | Privacy discrimination: Genomic data can be traced back to a name (p. 10). |

derived, the scenario team decided for the common number of three scenarios to be developed. These exemplary projections show that the incorporation of bibliometrics is useful for the cultivation of possible scenarios in two principal ways. First, it forces the consideration of technology-specific information and can reveal the influence of emerging or converging fields of technology. Second, it helps to avoid the consideration of implausible assumptions and to narrow the scenario funnel.

### 5.4. Cluster projections into consistent bundles of alternatives

To cluster projections, we used the common tool of the consistency matrix (Reibnitz, 1992; Gausemeier, 2009). Specifically, to bundle compatible projections, we assessed their consistency via pairwise comparisons. In this section, we demonstrate how the relative proximity of research fronts (Fig. 3) and comparison of research fronts with knowledge bases (Fig. 2) provides evidence related to consistent projections.

The "Mental Disorders" research front is located at a distance to the other research fronts. This suggests that the projections of the former are characterized by a neutral consistency related to all other technological projections. The "omics" technologies, including pharmacogenomics, genomics, and proteomics, have converged from several knowledge bases into a single research front. Therefore, we deemed all positive projections of the respective descriptors to be consistent. We made this same assumption for the "Number of Residents with Education in PM" descriptor.

"Nanomedicine" is still relatively far from other research fronts in terms of proximity. However, several articles in this cluster possess strong bibliographic coupling with articles in the central clusters, thereby indicating possible convergences with those clusters in the future. Therefore, we assessed the respective projections when heading in the same direction as consistent. The same was true for "Metabolomics."

### 5.5. Describe scenarios

In this step, we integrated the consistent bundles of alternatives into three possible scenarios for the future of personalized medicine in 15 to 20 years. In the following sections, we illustrate the nature of these three scenarios, respectively titled as the "Regulatory Issues Scenario," the "Technology Scenario," and the "Business Model Scenario."

By integrating the results of the bibliometric analysis in this step, core articles from the knowledge bases and especially from the research fronts informed our scenarios. The core articles represent frequently cited articles, review articles, or articles related to future opportunities and risks. We identified these using each actor's degree centrality (Dröge et al., 2000) and through a systematic screening of all titles and abstracts. Ultimately, it was necessary to carefully read the identified articles to glean detailed information. In the following scenario descriptions, we integrated select core articles to demonstrate how information from the bibliometric analysis enriched the scenario team's body of knowledge.

#### 5.5.1. Scenario 1: The "Regulatory Issues Scenario"

In this scenario, high regulatory barriers in the European Union have restricted the speedy implementation of PM methods into practice. As a result, PM has not achieved once-

**Table 7**
Input from bibliometric analysis into Scenario 2.

| Main components of scenario technique | Article | Research field | Information from article |
|---|---|---|---|
| (1) "Omics" technologies | Aboud and Weiss (2013) | Metabolomics | Powerful tool for detecting and analyzing targets (cancer metabolome), especially in combination with other "omics" (p. 139) and biomarkers (p. 140). |
| | Regierer et al. (2013) | All '"omics" technologies | Comprehensively analyzing the entire biological system by integrating all available biological data (proteins, genes, metabolites) enables a pro-active approach, thereby shifting to a preventive "system medicine" (p. 5-6, 15). |
| (2) DNA sequencing technologies | (McCarthy et al., 2013) | Genomic medicine | Understanding the health implications of genetic variation uncovered through genome sequencing has to be improved (p. 11). |
| | Cordero and Ashley (2012) | Whole-genome sequencing | Whole-genome sequencing to personalized diagnosis and therapeutics need an exponential decline in sequencing costs and constant improvement in related technologies to allow for the use of a patient's full genetic profile (p. 1001). |
| (3) Nanomedicine | Amir-Aslani and Mangematin (2010) | Biomarkers | Biomarkers are a tool for drug discovery and systematic development of personalized medication (p. 205) |
| | (Lammers et al., 2010) | Nanotheranostics | Nanomedicine enables theranostic approaches (i.e. systems and strategies in which disease diagnosis and therapy are combined [p. 1899]). |
| (4) Personalized therapeutics | Amir-Aslani and Mangematin (2010) | Disease biomarkers | Theranostics as "highly specific tests that allow for the diagnosis of the disease, but to administer the most appropriate treatment regimen" ((Amir-Aslani and Mangematin, 2010, p. 203)). |
| | Miller and O'Callaghan (2013) | Disease biomarkers | Personalization in drug choice can be achieved in major depressive disorder (p. 34). |
| (5) ICT | Regierer et al. (2013) | System medicine | Increasing amount of diagnostic data: real-time data collection, transfer, and processing is needed (p. 20). |
| | Louca (2012) | Health care system | ICT is the most important tool to translate PM into clinical practice. (p. 212) Laboratory-on-chip technology and bio-nanotechnology enables a personalized diagnostic and medication (p. 211). |
| | McCarthy et al. (2013) | Genome medicine | Diffusion of technology knowledge by using genome databases for tracking available tests to guide practitioners (p. 8). Plug-and-play bioinformatics support tools (p. 9). Personal health records for self-management of genetic data such as Microsoft Health Vault (p. 9). |

optimistic expectations. Examples of regulatory barriers include (1) a scarce public funding, (2) poor education of health professionals in the application of technologies and methods, (3) a lack of studies analyzing cost-effectiveness, (4) a lack of studies on the proper assessment of risks and benefits for patients, and (5) a regulatory framework deficient in terms of privacy rights.

Table 6 provides an overview of the core articles we identified and the information we incorporated into the assumptions outlined above.

### 5.5.2. Scenario 2: The "Technology Scenario"

This scenario describes personalized medicine as a field characterized by the convergence of several technologies in the medical care industry. The convergence of different technologies has led to a "systems medicine" representing a holistic diagnostic approach of preventive medicine. All body-related data is used to recognize diseases before they emerge. Technologies, like those pervasive in the "omics" technologies (i.e., metabolomics, genomics, pharmacogenomics), DNA sequencing technologies, and nanomedicine technologies have overcome technical, legal, and ethical barriers and are used in combination. Clinical research and diagnostics has also converged to allow for the development of personalized drugs, which can then be used to personalize drug-based therapies. In addition, ICT technologies have catalyzed the translation of research findings to clinical practice and the realization of holistic data management has revolutionized the entire health care system.

Table 7 provides an overview of core articles and the information incorporated into related assumptions.

### 5.5.3. Scenario 3: The "Business Model Scenario"

In this scenario, the health care system has fundamentally changed due to the lack of systematic public funding. The financial burden of diagnostics from PM remains substantial. In addition, some large pharmaceutical companies have prevented more widespread diffusion of personalized medicine approaches to protect income streams derived from the sale of blockbuster drugs. As a consequence, a new business model has evolved in the health care market in which personalized medicine is accessible to only a small fraction of the population. Single companies operate as "solution providers" that support consumer-driven PM research. These companies have built a network of research laboratories, clinics, private investors, ICT organizations, and health insurance providers. Reimbursement policies may differ from company-to-company and patient-to-patient. Research on personalized medicine, particularly its application, as well as the use of the collected patient data are exclusive to network members.

Table 8 provides an overview of the core articles and information incorporated into assumptions about this scenario.

## 5.6. Identify disruptive events and their effects on the scenarios

To discuss possible "black swans" and evaluate the robustness of the scenarios, we identified possible disruptive events and determined the effects they might have on our scenarios. Although identifying disruptive events can involve the consideration of multiple sources of inspiration, it remains highly speculative. It is impossible to know for sure if emerging issues will develop into full-blown disruptive events. Regardless, the integration of this step into the scenario technique supported by

**Table 8**
Input from bibliometric analysis into Scenario 3.

| Main components scenario technique | Article | Research field | Information from article |
|---|---|---|---|
| (1) Lack of systematic public funding | McCarthy et al. (2013) | Genome medicine | The financial burden of the development of personalized diagnostics is huge. As a consequence, public and private consortia have emerged to pool resources (p. 8) |
| (2) Prohibition of personalized medicine | Offit (2011) | Personalized medicine and its evolution | Large pharmaceutical companies have come to view genetically targeted therapy as an economic challenge with the need to modernize the business model associated with profitable, blockbuster drugs (p. 8-9). |
| | Mittra and Tait (2012) | Medicine business models | Blockbuster drugs are no longer the appropriate business model in the medicine business. Drugs must be changed into "niche-busters" (p. 709) |
| (3) Network building and "solution providers" | Frueh (2013) | Translation of PM into practice | New partnerships in the test-design and analysis of effectiveness are needed (p. 3-4). |
| | Faulkner et al. (2012) | Development and reimbursement of PM | Low-priced diagnostics have led to the drug-development companies to fund diagnostic research. This indicates that the strengthening of the partnership between diagnostics and drug development is imminent (p. 8) |
| | Mittra and Tait (2012) | Medicine business models | Co-development of therapy and diagnostics is needed (p. 709). |
| | Lester (2009) | Health care system | Each stakeholder in the health care system (drug companies, diagnostics, providers, patients) must change its business model and build networks (p. 3). |
| | Lester (2009) | Health care system | The most important issue for providers is creating a process for facilitating the integration of new technologies (p. 6). |

bibliometric information helps to cope with the disruptive events that might occur.

Using information gleaned from analyzing the research fronts, we detected a number of crucial challenges regarding the future of PM in the health care system. First, the pharmaceutical industry must seek to transition from a business model that focuses on a single, cash-cow, blockbuster drug to a new, flexible business model geared towards developing individual drug therapies (Offit, 2011). Cost-effective technologies that ease the production of personalized therapeutics can help solve this dilemma. One possible disruptive event interfering with this development would be the realization of a cost-efficient therapeutic approach that facilitates an efficient "super pill" that is suitable for all kind of diseases. Nanomedicine technologies have the potential to revolutionize individual diagnostic approaches, and can therefore help bring these therapies out of science fiction and into reality. As such, the cost-efficient production of personalized therapeutics would have a particularly strong effect on Scenarios 1 and 2. In addition, personalized therapeutics would significantly accelerate Scenario 3.

Finally, we imagined possible disruptive events in terms of regulatory control. In this context, it seems that a recent debate regarding a free trade agreement between Europe and the United States will affect all three scenarios. Specifically, this debate may change fundamental conditions in the healthcare sector (e.g., health insurance, pharmaceutical approval processes).

In this step, information from the bibliographic network offers a framework to make assumptions about future events more accurate. Despite the utility of bibliometrics, however, the scenario team deemed creativity-intensive activities (e.g., brainwriting) most important for predicting disruptive events.

### *5.7. Identify emerging technologies*

By utilizing the scenario technique in the context of technology foresight, we primarily sought to (1) identify emerging technologies, and (2) integrate them into the scenarios. This task represents the most crucial step in the eight-step foresight approach outlined in Section 3. To perform this task, we utilized common brainstorming methods and term frequency analysis to complement the results of the bibliometric analysis. The brainstorming methods consisted of (1) searching for analogies from past cross-industry innovations (e.g., imaging technologies (Doi, 2006), 3D-printing technologies for tissue engineering (Richards et al., 2013; Liu et al., 2013)), (2) searching beyond the usual context to detect the convergence of two research fields (e.g., nanomedicine), and (3) considering unsolved problems in the field of PM and thinking of possible solutions. The latter brought up emerging technologies that can overcome the side effects of traditional therapies, such as t-cell-based vaccines for cancer patients (Tumor Vaccine Group, n.a.; June, 2007). Some articles in the bibliographically coupled network produced evidence for the appearance of immunology in the field of personalized medicine (Leong et al., 2010; Andrade, 2009).

Results from the term frequency analysis confirmed that most academic attention is paid to cancer diagnostics with a particular focus on breast and lung cancers. Additionally, we detected multiple terms related to immunology (e.g., vaccines), thereby supporting the assumption that cancer vaccines are an emergent technology.

In addition, we used information derived from the research fronts to detect emerging technologies. Below, we offer a synopsis of the emerging technologies we identified using bibliometrics. Generally speaking, the foresight timeframe defined in step one of the scenario technique determines the degree of specificity with which these technologies can be described. When looking 20 years into the future, even technology experts in a research field have trouble to predict in detail fundamental characteristics of the research field under investigation. This dilemma can be resolved through a shift of focus from single technologies to fields of technology. Because we focus on the demonstration of a combined method, we offer a relatively brief description of potential emerging technologies.

Through an integration of key information from the co-citation and bibliographically coupled networks, we identified the following emerging technologies:

• Nanomedicine technology

By referring to the co-citation network comparing it to the respective research front, nanomedicine has gained interest in the scientific community. Although it has yet to converge with other research fields related to PM, the increasing number of papers on nanomedicine leads to the conclusion that some convergence will occur in the near future.

• Diagnostic methods for mental disorders and infectious diseases

In the bibliographically coupled network, the emergence of the mental disorders cluster signifies a shift in focus away from cancer diagnostics (Miller and O'Callaghan, 2013). In addition to mental disorders, the analysis of core articles suggests that the market of therapeutics for infectious diseases will increase (McCarthy et al., 2013; Amir-Aslani and Mangematin, 2010).

• Metabolomics

The knowledge bases of proteomics and pharmacogenomics have converged into one research front called “Cancer Genotyping” (Aboud and Weiss, 2013). The imminent convergence of metabolomics into the genome sequencing technologies cluster that can be seen in the bibliographically coupled network may yield more comprehensive diagnostic methods, as well as an increased study of interdependence between the different “omics” technologies.

• Sequencing technologies for clinical practice

The knowledge bases “Molecular Diagnostics & DNA Sequencing” and “Cancer Diagnostics & Biomarkers” have developed over time to form the research front clusters “Methods & Technologies in Cancer Diagnosis,” “Genotyping & Cancer Classification,” and “Translation into Clinical Practice.” The increasing number of papers addressing the future translation of sequencing technologies into clinical practice suggests improvement in the usability and cost-efficiency of such technologies. As such, the focus here is on making existing sequencing technologies affordable and easy-to-use for residents and practitioners.

• ICT

Core articles in the “Genotyping and Cancer Classification,” “Methods & Technologies in Cancer Diagnosis,” and “Translation into Clinical Practice” research fronts are related to how information and communication technology enables the translation of PM diagnostics and therapeutics into clinical practice. Stakeholders of PM, especially related regulatory entities, must take into account big data management in their future business model (e.g., in regard to privacy issues).

Clearly, research fronts serve to indicate what technologies may emerge in the future. In combination with scenario technique, the characteristics of these technologies in different future states as well as their effects on these states must be discussed. To understand the implications of these technologies for strategic management, it is critical to identify technologies that perform best in each scenario. Therefore, we assessed the respective effects of each emerging technology on each scenario.

In the “Regulatory Issue Scenario” restrictive processes that hinder the approval of pharmaceuticals can reduce the amount of research related to those pharmaceuticals. As a result, translating even well-established technologies (e.g., sequencing technologies) into clinical practice and making them cost-efficient could remain an unlikely possibility in the near future. Because of a general lack of public funding, proper conditions do not exist and research projects related to new approaches have thus far failed to achieve these goals. Therefore, this scenario will not result in the fast development of recent emerging technologies (e.g., nanomedicine, diagnostics in mental disorders, immunology-focused cancer treatments).

It is clear that Scenario 2 provides a setting in which PM research efforts will be facilitated. As such, in Scenario 2, the cost-effectiveness of genome- and molecular-based technology will be achieved in the very near future. Moreover, the relatively novel approaches (e.g., immunology) will also undergo development and research efforts regarding rare diseases have a chance to flourish in this scenario. In addition, ICT will positively affect the translation of PM research into clinical practice in the near future.

This latter point is also true for Scenario 3 even if PM is exclusive for the participants of the PM network. In this scenario, private funding represents the key financial driver for research efforts. More specifically, customer-driven funding may incite greater interest in research geared towards fighting rare diseases. As a result, technologies related to diagnostics and therapies associated with rare cancer types may develop faster in Scenario 3 than in the other scenarios.

In sum, in this crucial step of the scenario technique, the added value of the proposed method combination becomes obvious. Bibliometrics offers evidence related to emerging technologies and yields information regarding the near future. The information gained from the bibliometric methods set clear boundaries for the scenario development and helped to avoid implausible speculation regarding technological developments in the long term. Owing to the utility of the methods described here, the scenario team was able to prioritize fields of technology based on their respective effects on and robustness in each of the scenarios.

### *5.8. Explore the implications for technology strategy and derive plans for action*

At this point in the process, the scenario team adopted the perspective of a specific stakeholder to explore the implications of the scenarios for strategic management. In the context of PM, this stakeholder could be a diagnostics company, a research laboratory, a pharmaceutical company, a hospital, or a health insurance company. By adopting the perspective of one of these stakeholders, the team was able to explore the implications of the scenarios, and the technologies that emerge therein, for future strategy development. More specifically, companies must review their technology strategies by (1) integrating the scenarios into their strategy planning, and (2) asking how emerging technologies would fit into their technology portfolio. In addition, companies must make decisions related to the make-or-buy of technologies, as well as the allocation of R&D resources.

Due to the number and variety of stakeholders, as well as the differential positions in the value-added chain, we illustrate how bibliometric analyses can support strategic decision-making on an exemplary level.

The research portfolio (Fig. 4) indicates how different topics emerge and evolve. Most obviously, the scientific community has intensely debated cancer diagnostics and barriers to translating PM research into clinical practice. This may support the notion that pharmaceutical companies must review their extant business models and search for partnerships with research laboratories and small diagnostics companies. In doing so, the pharmaceutical companies can shift their position in the value chain closer to PM-related innovative technologies. Still, research topics that have declined in interest within the scientific community remain worthy of further analysis; they may have reached maturity and are therefore ready to be migrated into clinical practice.

In addition to the research portfolio, the co-authorship network helps to identify key expert clusters in specific research fields that may be amenable to future collaboration. The network also reveals the degree of scientific cooperation among researchers. In a co-authorship network, two organizations are proximally close if authors from two organizations have published articles together. In the case of PM, co-authorship among individuals in different organizations is relatively rare. However, we identified some large clusters (e.g., Stanford University, Harvard Medical School). We found no obvious research clusters within Europe. This supported the assumption that the research in the U.S. (and Canada) is more organized and cooperative than research in Europe.

As with the previous steps in the scenario analysis, bibliometrics supported the identification of emerging technologies, key experts, and potential research partners. However, when deciding on resource allocation, the scenario team considered the specific company's situation and internal factors (e.g., its technological capabilities) to be the most important. It is clear that due to its facilitating effect on the identification of emerging issues and alternative development paths, bibliometrics plays a complementary role in this step.

## 6. Conclusion and suggestions for future research

In this paper, we have highlighted the application of a method that combines the scenario technique with bibliometric analysis. In doing so, we have achieved three research objectives. First, after identifying research gaps in the literature (Section 2), we described an eight-step scenario approach based on crucial approaches from scientific literature and specialized it for use in the context of technology foresight (Section 3). Second, we proposed a novel method combination whereby bibliometric analysis (Section 4) is combined with the scenario technique. We showed how information from the bibliometric analysis can be used in every step of scenario technique. To illustrate its utility in practice, we reported the findings of a case study regarding the research field of personalized medicine (PM) (Section 5). In doing so, we addressed our third research objective: providing a series of guidelines for practitioners. In addition, in the case study we validated how bibliometrics supports the entire visioning process. The bibliometric results we integrated include knowledge bases, research fronts, the research portfolio, core articles, a network of organizations, term frequencies, and basic results from descriptive statistics. We developed three scenarios, a "Regulatory Issue Scenario", a "Technology Scenario", and a "Business Model Scenario". We also discussed potential disruptive events that could affect these scenarios. More specifically, we identified emerging technologies and postulated about their respective effects on the scenarios. Finally, we showed on an exemplary level how bibliometrics can provide useful information to inform strategy development.

Overall, the key benefit associated with the novel combined method is the integration of scientific information that complements or exceeds the scenario team's and experts' knowledge bases. In particular, the evaluation of vast technology-specific information allows for the identification of emerging technologies. Beyond that, the method combination is a powerful foresight tool rendering projections for future states more precise when narrowing the scenario funnel.

The case study presented in this paper illustrates that bibliometric information requires intensive discussion among all members of the scenario team. Given this, combining methodological knowledge regarding bibliometric analysis and scenario technique with subject matter knowledge optimizes the results. Although this paper provides several theoretical, methodological, and practical contributions, the method combination suffers from two key limitations. First, the performance of a bibliometric analysis can be a time-consuming endeavor. To assure optimal results when combined with the scenario technique, bibliometric information should be prepared beforehand by a scenario team member with experience in bibliometrics. Second, it is clear that the combination of bibliometrics with the scenario technique is more useful in some steps than others. For example, steps 6 (identification of disruptive events) and 8 (exploration of implications on technology-based strategy) do not benefit greatly from the addition of bibliometric information. Still, bibliometric analyses can be beneficial for the scenario technique as a whole.

Finally, there are several avenues for future work that can improve method combinations for the purpose of conducting technology foresight and promote their translation into practice:

- To allow for more complex combinations of methods (e.g., bibliometrics, scenario technique and system dynamics), future research should focus on expanding and improving ICT tools and foresight support systems.
- Because practitioners appreciate case studies as illustrations of methodology applications, researchers should perform more case study research in the field of technology foresight to facilitate the transfer of methodologies from academia into practice.
- To further evaluate the proposed combined method, it is crucial to explore its application in different settings and different research fields beyond PM.

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