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Abstract: This paper highlights technology roadmapping issues for advanced industries, in particular with regard to disruptive technologies. It examines the currently available range of technology watch techniques and considers the potential offered by the emerging Semantic Web. This paper introduces the technology watch research work of the University of Nottingham's Responsive Manufacturing Group and describes a database-supported process that has been applied in the UK's aerospace industry. It also describes an ontology-based technology watch system that has been applied in prototype form at a major aerospace manufacturer. A method has been developed to evaluate the level of potential threat that an emerging technology represents and to attach a value to a technology watch project that alleviates that threat level. This paper concludes that an effective technology watch function can significantly mitigate the risks that high technology companies face.

Keywords: strategic technology planning; technology watch; technology roadmapping; ontologies; Semantic Web.

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1 Introduction

The recent advances of India and China, in terms of education, technology and infrastructure, have dramatically increased the global availability of physical resources and skilled human resources. This has resulted in increasing levels of global competition and has contributed to accelerating rates of technology change and corresponding increases in Research and Development (R&D) costs. At the same time this globalisation offers enhanced marketing opportunities to successful international companies.

In addition to competition-based price pressures, companies face customer demands for better performance, shorter product life cycles, compressed times-to-market and increasing regulatory legislation. In this environment, companies must focus on both their current markets and their potential future markets, and must also be able to respond rapidly to unforeseen changes in technology and market conditions, that is, they must be responsive to change, irrespective of its source.

To summarise, high technology companies face a combination of increasing rates of technology change, shorter product life cycles and increasing costs of R&D. Whereas users of technology such as service provider companies can wait (and plan) for new technologies to be developed by suppliers, typical high technology companies are under constant threat of being undermined by the technology developments of competitors. They must ensure that they have ownership of at least part of any new technology that is of key importance to their success, that is, they must gain Intellectual Property Rights (IPR) that they can use to block or trade with competitors. These companies must therefore be aware of emerging technologies and must select carefully which of these technologies to invest in. This requires an effective approach to technology tracking and acquisition.

2 Tracking new technologies

For a high technology company, investment in a new technology is a strategic decision that can have a major impact on the company's performance for many years. The wrong timing or choice in technology investment (e.g. due to the inherent limitations of the technology, lack of relevance to the company's products or preexisting competitor IPR) can result in low profits and obsolete products.

Intelligence-based assessments of future technology developments can reveal potential threats and opportunities; if these assessments are used to support a company's strategic technology planning process, then the company can anticipate threats and opportunities arising from such developments and can react in time to benefit from them.

2.1 National and sector level roadmaps and roadmapping activities

Sector-level technology roadmaps have been developed for many industries with the express purpose of capturing expectations or intentions within those industries. A prime example of such a roadmap is the semiconductor industry's International Technology Roadmap for Semiconductors (ITRS) (SIA, 2005). The ITRS provides extremely detailed, regularly updated forecasts of developments in the performances, packaging, modelling, testing, etc., of semiconductor components, products and processing equipment. The high level of detail and remarkable predictive power (to-date) of this roadmap has only been possible because of its limited focus (primarily on silicon), the predictive success of Moore's Law (Moore, 1965) and the resulting partially self-fulfilling expectations of the semiconductor industry.

Most technologically advanced industries, for example aerospace, draw their technologies from many areas of materials and processes and therefore do not have the benefit of as clear a view of the future as that of the semiconductor industry. Their roadmaps are typically of a more general nature, referring to future markets, legislative constraints, prices, etc.

Typical examples of aerospace industry roadmaps include the UK's Foresight *Aerospace Manufacturing 2020* (NACAM, 2001) and the European Commission's *European Aeronautics: A Vision for 2020* (Group of Personalities, 2001). However, in order to obtain useful information about potential technology developments, aerospace companies have to track many non-aerospace roadmaps. The US Air Force supported *Aluminium Metal Matrix Composites Roadmap* (Technologies Research Corporation, 2002) and the US Department of Energy supported *Advanced Ceramics Technology Roadmap* (Energetics Incorporated & Richerson and Associates, 2000) are two out of a hundred or more materials technology roadmaps of potential relevance to aerospace companies.

2.2 Disruptive technologies and the need for company-level roadmaps

Whether produced by industry-led working groups or government-sponsored 'foresight' teams, an industrial sector technology roadmap typically represents the views of the largest and most successful companies in that sector. Such companies are typically highly focused on their *current* key customers and markets. However, this high degree of focus represents the potential 'Achilles heel' of many sector technology roadmaps; emerging technologies that do not currently demonstrate potential benefits for the most profitable section of the market may be overlooked. Therefore, companies that rely excessively on such sector roadmaps (rather than producing their own roadmaps) may fail to detect agile newcomers that obtain a foothold in the sector's markets with cheaper, better or faster technologies that subsequently threaten existing producers.

Ashton and Stacey (1995) provide a useful account of technology threats and opportunities. Clayton Christensen (1997) uses the term 'disruptive technology' to describe lower cost, initially lower performing, new technologies (or new *applications* of technologies) that are often introduced by new market entrants. Kostoff et al. (2004) describe a systematic approach for the identification of potentially disruptive technologies and the development and implementation of such technologies in products.

In a typical example of disruption, the new product (based on an emerging technology) initially attracts only the least performance-critical, low margin market segments and thus passes 'below the radar' of the industrial leaders who typically participate in industry sector roadmapping exercises. However, as the technology behind the product is developed, it delivers improved products that increasingly displace the preexisting high performance, high margin products; the former market leaders are either destroyed or forced out of the market. The old products are typically at the top of their '*S*' curves (Christensen, 1997, p.39), where only marginal improvements can be made, whereas the new technology is near the bottom of its '*S*' curve and major increases in performance can be achieved.

The implications of the above comments are that most industrial sector roadmaps have significant limitations in terms of their predictive power and should be regarded as just one of the several forms of input to an individual technology company's technology planning activities. Each high technology company has a unique combination of strengths, weaknesses, products, processes and customers and is therefore uniquely affected by technology-based opportunities and threats. As a result, each company needs to collect technology-related information of specific relevance to it, based on its current and planned products, processes and markets and to take this information into account when planning new R&D programmes.

2.3 A continuous technology watch activity

The R&D programmes of most high technology companies are the result of annually-occurring internal project submission, evaluation and selection activities, the timing and targets of which may be influenced by government R&D agendas and grants. However, with the present accelerating rate of technology change, it is not realistic merely to evaluate technology-based developments on an annual basis. A growing number of companies use internal and external resources to track relevant technologies and competitors in order to inform themselves of potentially threatening or beneficial developments, that is, they carry out a continuous technology watch activity.

3 Technology watch tools and techniques

Bibliometric analysis has been used for many years to develop Science and Technology (S&T) performance indicators, based on counts of publications, citations and patents (Narin et al., 1994). These bibliometrics-based performance indicators have been used for measuring R&D impact (Melkers, 1993) and for ranking research organisations, for example as in the UK universities' *Research Assessment Exercises*, but they have been found to be also useful for foresight and horizon scanning exercises, that is, for technology watch at the national level.

Data mining, which searches for potentially interesting patterns and correlations in datasets, was originally utilised primarily for sales and marketing purposes. However, text mining (or textual data mining), a development of data mining, can be utilised to extract intelligence about S&T developments from any electronic text sources. The resulting information has obvious applications at the national level, enabling comparisons to be made between the research outputs of various countries or regions in a range of disciplines. Losiewicz et al. (2000) provides a useful description of the five major steps involved in text mining and its application to support S&T management.

The above methods do not use significant intelligence in the form of semantics or pragmatics in order to target their search areas in order to reduce the corresponding amount of data processing and volume of outputs. Whereas their outputs are useful at the national or regional level and can assist government agencies in the allocation of R&D resources, they are less helpful at the level of the individual enterprise.

The Georgia Institute of Technology's *Technology Opportunities Analysis* (TOA) approach is an example of an effective text mining system that supports some degree of intelligent processing. This enables improved precision of outputs to match the needs of an enterprise's technology management; a description of the TOA process can be found in Zhu et al. (1999). The VantagePoint software system has been developed to support TOA and an example of its application can be found in Porter (2005).

Most high technology enterprises have a limited range of key technologies and products and serve clearly defined markets. Their technology managers can, with assistance, analyse the underlying functionalities of their products and processes and define the conditions or scenarios that may trigger significant or disruptive changes. The prior development of ontologies, threat and opportunity-based scenarios, etc., would enable improved control and pruning of searches and much reduced output of material for human assessment.

The University of Sheffield's h-Techsight Knowledge Management Portal (KMP) is just one example of emerging web-enabled ontology-based methodologies (Maynard et al., 2005). An ontology-based representation of the enterprise's domain of interest is constructed and this is used to direct the search for and extraction of, knowledge from a range of web sources. Other examples of web-enabled ontology-based systems include the knowledge management platform of Banares-Alcantara et al. (2003) and that of Alani et al. (2003).

The ongoing development of the Semantic Web (Hendler et al., 2002) has significant ramifications for the effectiveness of intelligent retrieval systems. The Semantic Web is being designed with a view to automated knowledge retrieval and integration, which will simplify and improve the efficiency of the 'front end' of retrieval systems. However, the Semantic Web is not designed to enable the expression of complex relationships and structures such as those that occur in natural language.

The technology watch research described later in this paper is targeted at the development of methodologies for application at the enterprise level and it is therefore the ontology-based approach that offers the greatest potential for effective solutions.

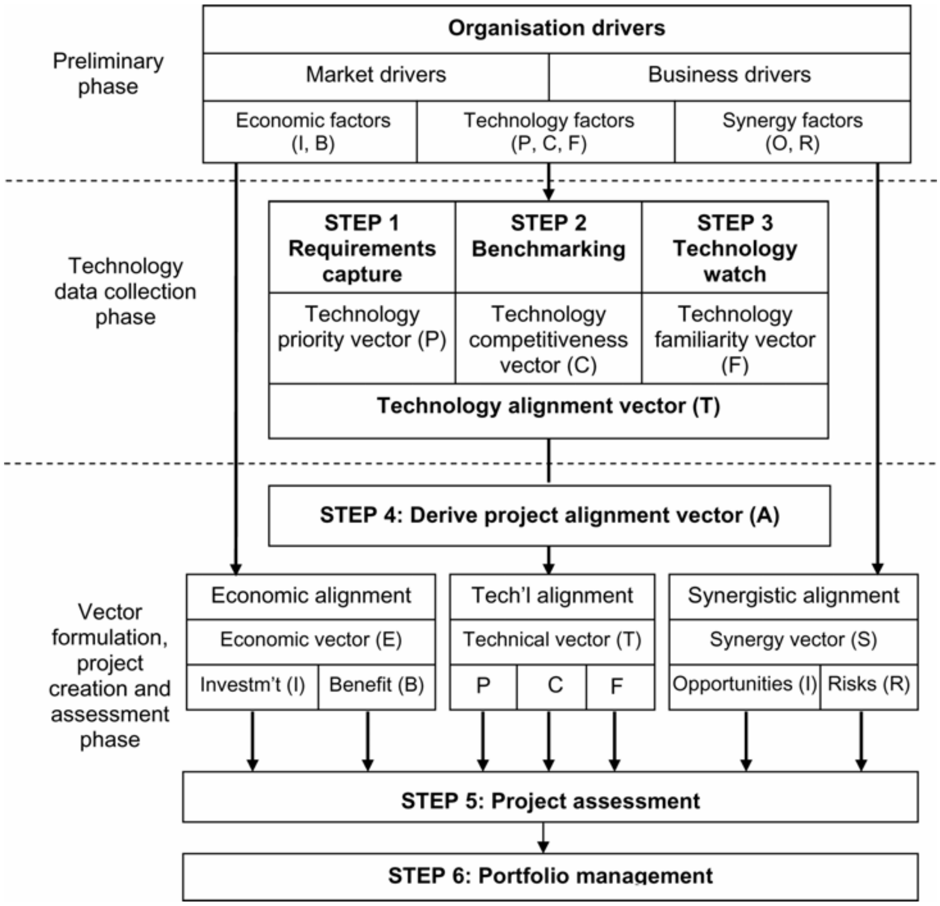
4 Technology watch research at the University of Nottingham

Researchers in the University of Nottingham's Responsive Manufacturing Group have developed an enterprise-level technology roadmapping methodology and applied it at industrial collaborator companies (Gindy et al., 2006a,b).

Based in part on feedback from industry, a comprehensive database-supported version, the Strategic Technology Alignment Roadmapping (STAR) methodology, is now being developed. This methodology provides software-supported steps, from the collection of company business data (market and business drivers, products, etc.) through to project evaluation and ranking and the creation of a balanced portfolio for the enterprise. Figure 1 illustrates the main components of STAR; as can be seen from the figure's 'technology data collection phase', technology watch is one of the three input modules of STAR.

The meanings and scope of activities within the field of technology acquisition are changing as improved understandings of the contributory factors are gained. However, it is useful to have working definitions of the major components. The current working definition of technology watch used by the Nottingham researchers is "the set of activities that enables organisations to identify and monitor new developments in technology associated with the products, processes and markets of concern to them".

Figure 1 Block diagram of the STAR technology roadmapping methodology



The University of Nottingham researchers are carrying out technology watch research activities to meet a range of requirements, from near-term delivery of practical solutions for the STAR methodology, to long-term research into pragmatics-based methodologies that will require advanced logic programming tools. These research activities are described further in the following subsections.

4.1 Information sources

Technology watch information arises from many sources, both internal and external to the organisation. The Responsive Manufacturing Group researchers carried out an exercise to determine the range, forms and volume of information of potential value for technology watch purposes. This exercise encompassed a range of activities, in particular:

- conventional literature surveys
- brainstorming exercises within the research environment
- discussions with industrialists

- the examination of information on past technology company failures that are due at least in part to disruptive technologies, in order to determine what information had been available but had not acted upon (i.e. could successful action have been taken?).

From the discussions with industrial contacts, it is clear that much potentially useful technology-related material is gathered on an informal basis and that it is difficult to detect relationships between information from different sources that could together provide advanced warnings of technology-based threats.

Some degree of shared understanding of information sources and the development of simple rules to define scenario types and their supporting evidence would encourage the wider use of information and a more proactive approach to information gathering.

A summary of the common forms of internal and external information sources and types is presented below.

4.1.1 Internal information sources

Internally available sources of information are often underestimated. Many people within a high technology company maintain a personal interest in new technologies and many others will notice changes that may reflect technology-driven changes on the part of competitors.

Typical internal sources include:

- R&D engineers and scientists
- designers, manufacturing engineers
- shop floor operators
- sales and marketing personnel
- intranets, databases, business drivers, forecasts, company roadmaps
- feedback from technology watch system users (see Section 4.3).

Marketing or sales departments often receive potentially useful 'early warning' information that is unrecognised. For example, a loss of unimportant low margin customers may not trigger concern, but may be due to a new entrant poaching them with an alternative technology product. Data mining systems are very useful for detecting trends and can provide useful warnings of technology-led market changes.

4.1.2 External information sources

Typical external sources include:

- customers, competitors, suppliers and partners
- national government, European Union and international organisations (e.g. OECD, WHO or the UK's DTI)
- trade fairs, conferences, seminars
- publications (e.g. newspapers, magazines, trade journals, academic journals, patent office information sheets)
- the World Wide Web – this will become the dominant information source as it transforms (in part) into the Semantic Web.

Information of particular interest, irrespective of the source, might include:

- job vacancies, job losses and movements of key technical experts
- requests for tenders, contracts
- a flurry of patents in certain areas
- company takeovers.

Currently, the University of Nottingham's research team is concentrating on the internet/intranet as a source of technology (watch) information.

4.2 Technology watch for the STAR methodology

The team has developed a database-supported manually applicable technology watch process for use within its STAR (roadmapping) methodology. The database is common to the requirements capture, benchmarking and technology watch elements of STAR, thus enabling the capture and reuse of information.

This process involves the following steps:

1. *The identification of key technologies*: these technologies will have been placed within a manufacturing taxonomy during the preliminary phase of STAR (implementation and data collection, see Figure 1). Most of these technologies should have been identified as of key importance via the product/market-driven requirements capture exercises and the competitor-driven benchmarking exercises, see Figure 1, 'Technology data collection phase'. A team consisting of appropriate staff (e.g. R&D, design, engineering, marketing) will determine whether the list of key technologies is complete and whether any additional technologies (taking account of new product developments and legislative changes) need to be added to the list.

2. *The identification of these technologies' key properties*: the chosen technologies' general properties may be well known, but the key properties of importance to the company must be stated clearly.

3. *The identification of competing emerging technologies*: the key properties of (2), above, provide a basis for the identification of potentially competing or disruptive technologies. Detailed lists of sources are provided, including a large range of web sources, but this element is currently the least formalised part of the technology watch process.

4. *The application of the STAR technology data collection process to each of the selected emerging technologies*: this step-by-step approach includes the gathering of information on R&D, patents, applications, competitor interest, suppliers, displaced and alternative technologies, etc., from a range of internal and external sources. The output from this process is a standard structured 'emerging technology' report on each emerging technology and a summary report that covers all of the selected emerging technologies.

5. *The assessment of competing emerging technologies by a group of experts*: following receipt of the emerging technology reports, an in-house-developed software tool, which incorporates the Analytical Hierarchy Process (AHP) pair-wise comparison method, can be utilised to capture and store the results

of this ranking activity along with comments made by team members, in which case the results are stored in the STAR database. Alternatively, another approach, for example, Delphi or questionnaires (sent to internal experts and, potentially, academics and technology suppliers) can be used.

One of the issues that has come to the fore during the above work relates to the financial justification of technology watch activities; as such activities seldom produce a direct financial return, it is difficult to score them highly based on normal criteria. There is therefore a danger that formal project evaluation approaches, including the multifactor approach of STAR, will fail to fully highlight the importance of technology watch project proposals. One solution is to split the annual R&D budget and consider technology watch projects separately. An alternative solution is proposed at the end of Section 4.3, see 'Technology Threat and Opportunity Analysis (TTOA)-based project scoring'.

4.3 Long term technology watch research

Based on an analysis of existing approaches to technology watch and an evaluation of the technology watch process described in Section 4.2, the Nottingham STA Subgroup researchers made a decision to develop an ontology-based enterprise-level technology watch methodology. This work is described in Section 4.3.1.

Tests of STAR (including the technology watch process described in Section 4.2) on a range of industrial R&D projects have highlighted the current difficulties associated with producing an objective justification of any technology watch project. Therefore, the technology watch technology assessment approach is being developed to provide measures of the level of threat and the potential financial cost of inaction, as described in Section 4.3.2.

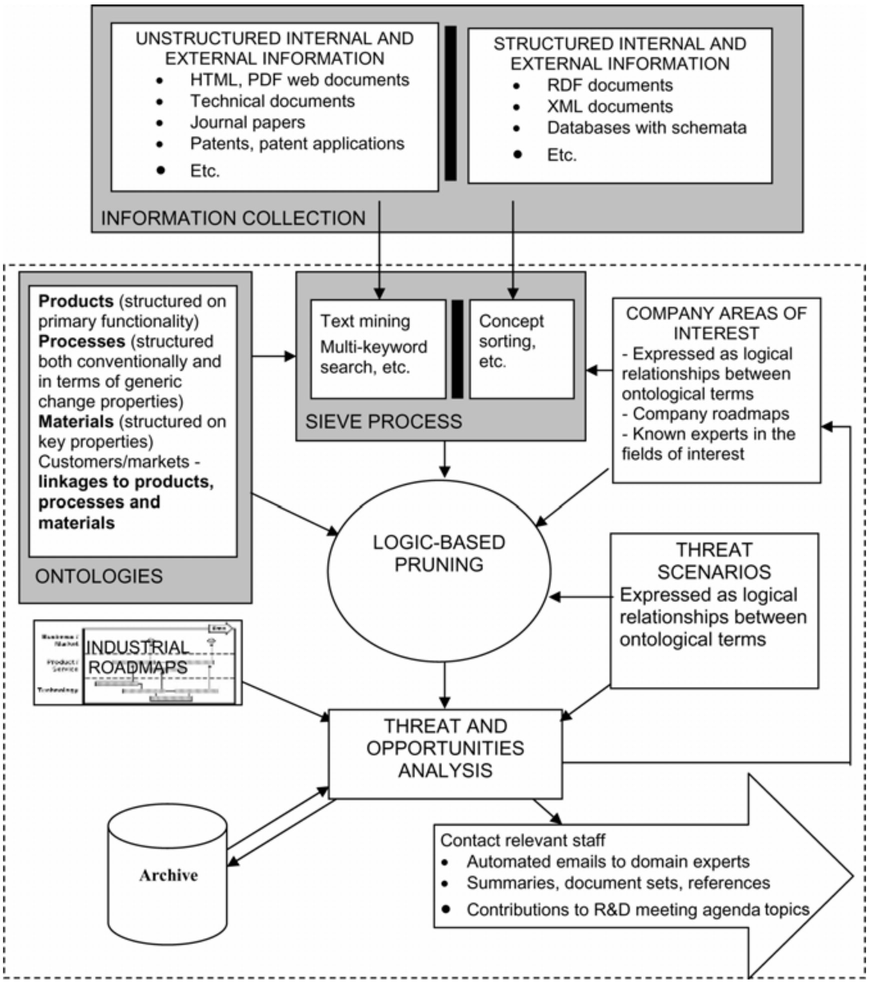
4.3.1 Ontology-based technology watch system

Product innovations, legislative changes, new technical standards, patents, research group activities, publications, movements of key knowledge workers, company takeovers and collaborative agreements all combine to produce a level of interaction complexity that cannot be represented by conventional information system structures. Therefore, the research group has taken the decision to produce technology-related knowledge representations based on ontologies and the logic modelling of relationships. A block diagram of the methodology is presented in Figure 2.

To-date, the researchers have developed ontological models, initially based on the Protégé ontology modelling system (Stanford, 2005) and more recently, on the OWL web ontology language (W3C, 2004). The Protégé OWL plug-in editor enables the building of ontologies for the Semantic Web; this is of particular benefit to the research, as the Semantic Web is expected to become the primary source of documented publicly available information. However, as stated in Section 3, the Semantic Web will not provide the complete solution. Therefore, logic systems with pragmatics-based natural language extensions are also being evaluated, including conceptual graph processing systems; see Sowa (1984) for an introduction to this topic.

The use of OWL enables the expression of logical relationships between generic types of concept and the expression of class membership constraints, for example necessary or necessary and sufficient conditions for membership of particular classes of concept. One of the areas of investigation is the creation of a class of 'alert' or 'alarm' situations; individuals (i.e. individual situations) are automatically placed as members of these classes when their (potentially very complex) sets of properties satisfy the appropriate conditions.

Figure 2 Block diagram of technology watch methodology



The researchers have 'handcrafted' situations associated with our industrial collaborators (whether potential threats or opportunities), each individually expressed as schemata using generic terms within the ontological environment; these schemata have then been rated in terms of their potential importance and if specific information is received that 'fills most of the boxes' of such a schema, an appropriate level of interest can be set or an alarm can be triggered if appropriate.

As part of the research, the potential contributions to threat sensitivity of concept *semantic distances* and *weighted schema matches* across multiple ontologies, are also being investigated.

The development of ontologies is typically an arduous manual activity that requires a large amount of labour on the part of knowledge experts. Few companies can afford to commit their own staff resources for the amount of time required to build detailed ontologies, nor can they justify the high costs of using external contractors. Therefore, the research team has examined several published ontologies with a view to the development of core ontologies that provide shortcuts to the creation of company-specific ontologies; several simple prototype generic ontologies, primarily in the areas of processes and products, have been constructed using the Protégé/OWL ontology tools; these ontologies are now being evaluated.

In addition to process and product-related ontologies, ontologies associated with customers/markets are being developed, but these are proving more difficult, as there are several 'views' associated with customers and markets that cannot be met by a single ontology.

4.3.2 Technology threat and opportunity analysis

As stated earlier, the technology watch element of the STAR methodology has posed several problems when attempting to score projects; it is very difficult to attribute point scores or monetary values to an emerging technology that is not represented in a company's current or planned repertoire of materials, processes or products.

In order to deal with this problem, for the STAR methodology and for future technology roadmapping systems, a prototype system has been developed for the evaluation of individual candidate emerging technologies. This has two elements – the evaluation of risks to the company and the scoring of proposed projects that would alleviate those risks.

4.3.2.1 The evaluation of risks to the company A basic TTOA scoring method has been developed, akin to the well-established Failure Mode and Effects Analysis (FMEA) method. As in FMEA, the higher the score, the greater the overall risk. The key factors are:

- *Probability of achieving maturity (P)*: the likelihood that (without our intervention) the emerging technology will be developed to its potential and applied in competitor companies.
- *Severity of threat (S)*: the potential loss to the company if this technology is developed to its full potential without a response from the company.
- *Our current inability to track and react to the threat (T)*: the likelihood, if we do not react soon, that this technology will develop without our knowledge and its IPR will belong to competitors. Note that the *minimum* score for this is set to '5' if we are not yet formally tracking the technology in question.

If the scales are each set from 1 to 10, this facilitates easy assessment of the level of threat, as the total technology priority number score (TPN = $P \times S \times T$) is out of 1000. The response to TPN scores would be related to company policies, but might be as follows:

- *TPN = 500 + (red)*: this indicates a need for immediate emergency action.
- *TPN = 200 to 500 (amber)*: this indicates a need to programme in a detailed technology watch activity leading to recommendations and a reduction in TPN.
- *TPN = 1 to 199 (green)*: no special actions are required.

Table 1 illustrates the results of a fictitious example of a TTOA of several developing technologies (materials/products and processes).

Table 1 Example TTOA table (from the aerospace sector)

T&O No.	*Item*	*Function*	*Threat and opportunity scenario*	*Risk*			
				P	*S*	*T*	*Total*
1	Ultra-low-stick nano-coating	Reduced adherence of dirt on airframe surfaces	Significant reduction in aircraft fuel consumption; application patents are crucial to protect future developments	9	7	6	378
2	Friction stir welding process	Joining materials of different thickness	Could largely replace riveting on airframes and drastically reduce airframe costs; USA and Japanese companies have submitted patents in this area, and the UK is significantly lagging	8	8	5	320
3	Engine noise reduction liners	Reduced take-off and landing noise	Enables more efficient aircraft approach paths at major airports, saving fuel and time	4	6	5	120

4.3.2.2 The scoring of technology watch project proposals A technology watch project is expected at least to increase significantly the capability to track the threat and hence reduce the value of T (e.g. from T_1 to T_2). A project score can be determined by subtracting the estimated post-project TPN score from the preproject TPN score (for the technology in question) and normalising the score.

If a monetary amount is substituted for the severity value (S), then $P \times T$ represents an estimated percentage likelihood that the company will suffer the financial loss S. The notional monetary return of the project can therefore be calculated as:

$$\pounds\text{Return} = \frac{\pounds S \times P\left(T_1 - T_2\right)}{100}$$

This can be used to provide a notional return to the enterprise and provide a financial justification for technology watch R&D projects. The enterprise may, for example, decide to value technology watch projects on the basis of 10 to 25% of the notional return.

The prototype assessment system incorporating the features described above provides simple deterministic figures for threat level and potential cost. However, more work is required:

- to incorporate measures of value other than risk reduction
- *To incorporate more sophisticated statistical measures*: it is intended to collect a body of test data with known historical outcomes from our industrial partners in order to test the current prototype and its future developments
- to integrate the work within the STAR methodology.

5 Industrial applications

The technology watch process of the STAR methodology has been applied to produce technology analyses for the UK's National Advisory Committee for Aerospace Manufacture (NACAM), and has also been used to produce the technology information sets for several workshops that formed the key inputs to a UK aerospace manufacturing white paper (Gindy et al., 2006a,b).

Elements of the ontology-based methodology have been applied at a major aerospace manufacturer in order to produce a roadmap for key manufacturing resources.

6 Conclusions

The globalisation of technology and the accelerating rate of technology change are exacerbating the risks that technology-orientated companies face. The drive to achieve responsiveness to customer needs (whether via agile processes or other means) must be mirrored by the achievement of responsiveness to changing product, material, process and information technologies.

Responsiveness to technology developments and a corresponding alleviation of technology-related risks, can be greatly improved by the utilisation of an effective enterprise-level technology watch function that provides early warnings and assessments of potential new technological developments.

The methodologies described in this paper are intended to enable proactive searches for information on potential technology-related developments and to assess these prior to supplying relevant personnel with information, appropriate 'alarm levels' and the associated reasoning. The initial technology watch methodology, built as part of the STAR methodology, requires significant manual effort, but several prototype ontologies have already been built to support the increasingly automated successors to this.

Several sophisticated ontology support tools are now available (most of them from other research organisations). These tools, when combined with emerging Semantic Web standards, offer considerable potential for the future development of automated technology watch facilities.

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