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The development perspectives of Physical Vapour Deposition technologies

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ABSTRACT

Purpose: The goal of this paper is presentation of comparative analysis results concerning the most perspective technology groups included in common called Physical Vapour Deposition (PVD) during the next 20 years.
Design/methodology/approach: In the framework of carried out research the value of the given technologies against the environment background has been determined and the development strategies for them has been defined. Moreover, for each from 10 analysed technology groups the technology roadmaps has been created. In carried out research source data collected during the three iterations of wide e-foresight expert research concerning the priority technologies in surface materials engineering area having the best development perspectives or key importance in industry has been used.
Findings: The carried out research pointed out the industrial importance of PVD technologies and good perspectives for these technology groups. Especially, the research results shows the best long-term development perspectives for CAD and RMS, however the strategic positions of PLD, ED-PVD, BARE, PPM, and IBAD are also promising.
Research limitations/implications: Research concerning PVD technologies constitute a part of a larger research project aimed at identifying, researching, and characterising the priority innovative technologies in the field of materials surface engineering.
Practical implications: The practical implementation possibilities of the given technology groups taking into account market products and industry branches in the last part of the paper are presented.
Originality/value: The novelty of this paper is to evaluate the value of PVD technologies in the background environment with their future development perspectives determination using custom computer integrated development prediction methodology.
Keywords: Thin & thick coatings; PVD; Technology e-Foresight; Technology roadmapping

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1. Introduction

The literature studies carried out indicate a great interest in the last decade in foresight research, including also widely-understood material engineering, being the subject of numerous projects implemented or carried out currently in the world [1-3] and in Poland [4-7]. An analysis of results and scope of these research combined with an observation of development tendencies in the industry was a basis for undertaking detailed foresight research aimed at identifying the priority innovation technologies and strategic development directions in the area of materials surface engineering. The task has been pursued since 2009 at the Institute of Engineering Materials and Biomaterials of the Silesian University of Technology [8]. Nearly 300 hundred independent domestic and foreign experts representing various scientific and business environments as well as state administration have participated in FORSURF technology foresight at the different stages of work. They have all filled in approx. 600 multi-question surveys and conducted thematic discussions in 7 Workshops. An analysis of development prospects has been performed in the initial phase of research for approx. 500 groups of detailed technologies including an issue steady state assessment, technological review and a strategic analysis with integrated methods. The following scientific and research methods were used for this purpose: trends extrapolation, environment scanning, STEEP analysis, SWOT analysis, expert panels, brainstorming, benchmarking, multi-criteria analysis, computer simulations and modelling, econometric and statistical analysis. 10 critical technologies with the best development prospects and/or of key importance for industry in the coming 20 years were selected in 14 thematic areas as a result of the works performed. A group of 140 critical technologies were analysed in detail for three iterations of the Delphi method according to the e-foresight concept [9] that utilises information technology including a virtual organisation, web platform and neural networks. Neural networks have been used in an innovative and experimental manner to conduct a cross impact analysis showing relationships between the analysed trends and events likely to occur in the future within the considered time period. The PVD technologies, evaluated highly by experts, are found among the thematic areas analysed. The article comprises the outcomes of foresight research based on the source data gathered concerning the identification of the future expected position of the PVD technologies against other materials surface engineering technologies and the importance and development prospects of the detailed 10 groups of the PVD technologies.

2. The PVD position compared to surface engineering development

The foresight investigations conducted (sample size: 198) have revealed that PVD technologies are significant for the development of overall materials surface engineering. According to 61% of respondents, PVD technologies are in the group of technologies with the best prospects of industrial applications, and 47% claim that numerous scientific and research works will be devoted to them in the nearest 20 years. In addition, over a half of the surveyed (48%) maintain that the thematic area "PVD technologies" is crucial and its significance should be absolutely on the rise so that an optimistic scenario of the country's development - "Race won" - can come true. 51% of the surveyed think that the importance of PVD technologies in relation to other materials surface engineering technologies will be growing, whereas 47% maintain it will remain on the same level, with only 2% claiming that the importance will diminish over the next 20 years. The results obtained point out, therefore, an anticipated major role of PVD technologies in fulfilling the optimistic scenario of developing the Polish economy at a macro and mezo scale.

3. Value and forecasted future of the PVD technologies

An assessment of the analysed PVD technologies' groups against the micro- and macro-environment and the resultant, recommended action strategy for this group of technologies has been presented graphically using a custom methodology [10] and source data acquired in the foresight research conducted. The research conducted uses a single-pole positive scale without zero called a universal scale of relative states [10], where 1 is a minimum rate and 10 an extraordinarily high rate. The following 10 groups of critical technologies selected at the earlier stage of foresight research were analysed:
(A) Cathodic Arc Deposition (CAD),
(B) Reactive Magnetron Sputtering (RMS),
(C) Pulse Plasma Method (PPM),
(D) Ion Beam Assisted Deposition (IBAD),
(E) Hot Hollow Cathode Deposition (HHCD),
(F) Electron Beam Physical Vapour Deposition (EB-PVD),
(G) Bias Activated Reactive Evaporation (BARE),
(H) Ionised Cluster Beam (ICB),
(I) Thermionic Arc Evaporation (TAE),
(J) Pulsed Laser Deposition (PLD).

The individual groups of the technologies were evaluated by experts according to their potential representing a realistic objective value of the specific group of technology and attractiveness reflecting the subjective perception of a specific technology by its potential users. The results were entered into one of the quarters of the **dendrological matrix of technology value** (Fig. 1) serving to visualise the objectivised values of the specific separated groups of technologies. Wide-stretching oak is the most promising quarter guaranteeing future success. Soaring cypress and rooted dwarf mountain pine may also ensure success provided an appropriate procedure is applied, which is unlikely or impossible for quaking aspen. The analysis has revealed that the groups of technologies (A) CAD, (B) RMS and (F) EB-PVD were classified to the most promising quarter of the matrix called wide-stretching oak. The groups of technologies (G) BARE, (C) PPM and (E) HHCD were found in the group rooted dwarf mountain pine encompassing solid, proven technologies with limited attractiveness. The attractive groups of technologies whose potential needs to be strengthened include (J) PLD and (D) IBAD placed in the quarter called soaring cypress. The least promising groups of technologies (I) TAE and (H) ICB are included in the quaking aspen area.

The metrological matrix of environment influence (Fig. 2) presents graphically the results of evaluation for the influence of external positive factors (opportunities) and negative factors (difficulties) on the technologies analysed. Each of the technologies groups assessed by the experts was included in one of the matrix quarters. Sunny spring illustrates the most favourable external situation ensuring future success. Rainy autumn corresponds to a neutral environment and hot summer to a stormy environment where the success of a technology is risky but feasible, as opposed to frosty winter. The results of the research show that an environment is most supportive for the following groups of technologies: (B) RMS, (A) CAD and (J) PLD included in a quarter called sunny spring. The groups of technologies (E) HHCD, (I) TAE and (H) ICB are accompanied by a stormy environment (hot summer) signifying the risk for their future development. The other groups of technologies are in a neutral environment called rainy autumn permitting their further steady progress.

The results of expert research visualised with the dendrological and meteorological matrix were at the next stage of scientific work entered into the **matrix of strategies for technologies** (Fig. 3) using a computer programme based on the previously formulated mathematic relations [10]. The matrix presents graphically a place of each group of technologies according to their value and environment influence intensity and identifies a recommended action strategy. The circles mark the strategic development prospects of a given group of technologies expressed in numbers using a universal scale of relative states. The results presented show that the groups of technologies (B) RMS and (A) CAD that should be developed, enhanced and implemented in industrial practice for achieving a spectacular success, have the best prospects of strategic development. An attractive group of technologies (J) PLD with limited potential should be investigated, improved and invested more using the prevailing robust economic market condition. It is expected, in relation to the group of technologies (F) EB PVD, that they will be successful with an attractive, stable technology at the expected market, and it is recommended at the same time that new markets, customer groups and products feasible for manufacture should be sought for. The manufacturers employing solid groups of technologies (C) PPM and (G) BARE should derive profits from implementing production in a stable, predictable environment and modernise and promote them to enhance attractiveness. A procedure recommended for (D) IBAD is to maximally exploit the favourable external conditions for implementing production using an attractive. technology combined with reinforcing its potential, and reinforcing attractiveness and matching the product to a customer's requirements is a strategy recommended for (E) HHCD. As far as the groups of technologies with the lowest rates and explored to a relatively smaller extent are concerned, i.e.: experimental (H) ICB and growth (I) TAE technologies, a risk assessment with an individual assessment of success potential is recommended. Surprising scenarios need to be taken in account in both cases, and a spectacular breakthrough is not excluded considering that the technologies are new and are found in a stormy environment.

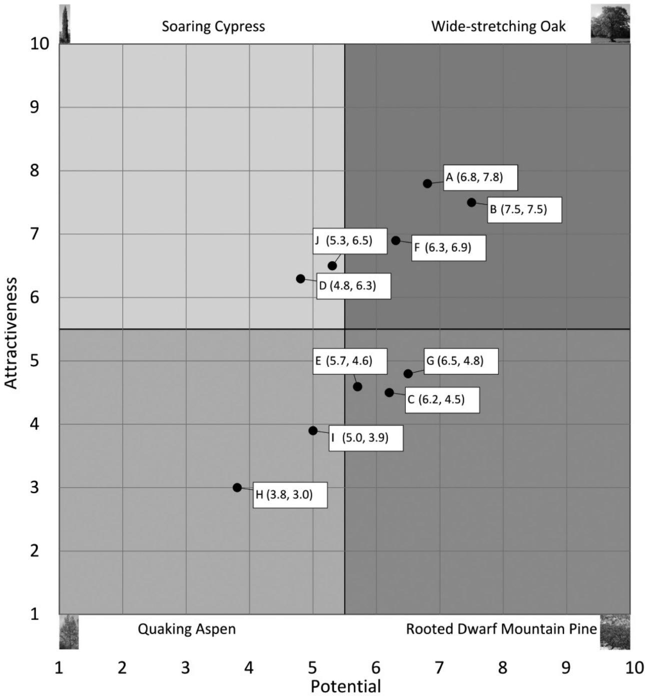

Fig. 1. The dendrological matrix of technology value prepared for PVD technologies thematic area

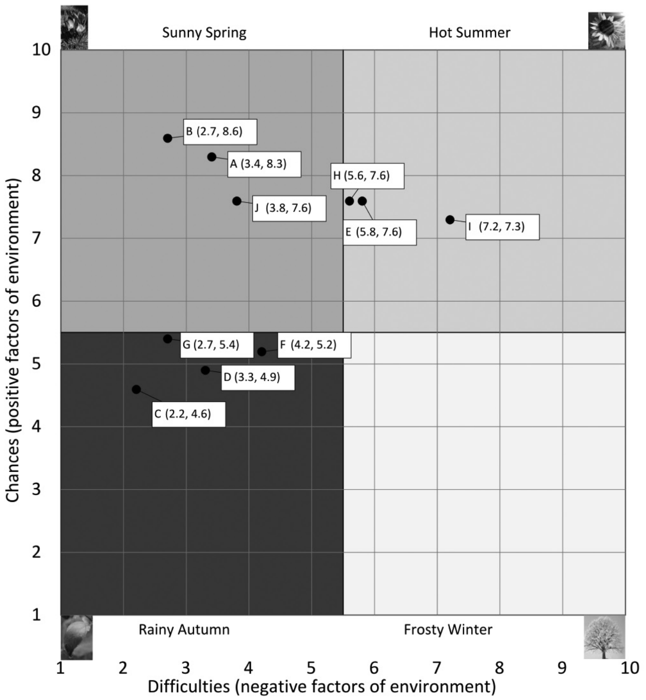

Fig. 2. The meteorological matrix of environment influence prepared for PVD technologies thematic area

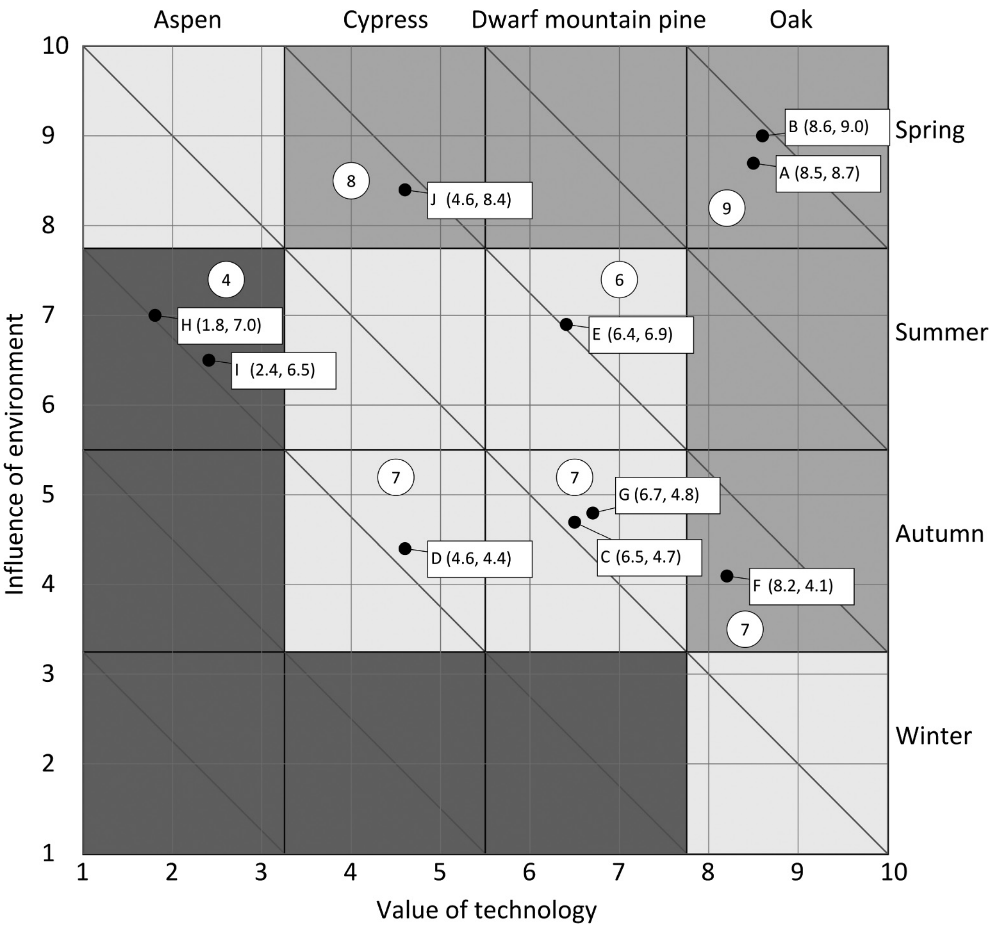

Fig. 3. The matrix of strategies for technologies prepared for "PVD technologies" thematic area

4. Industrial application possibilities and helpful analytical tools

Easy access to information concerning priority, innovation technologies is one of the prerequisites for improving the statistical level of technologies applied in the industry, especially in small- and medium-sized enterprises. It is, therefore, purposeful to create a compendium of concise knowledge facilitating a comparative analysis of the technologies according to key criteria for relevance and profitability of such technologies' implementation. In order to fulfil this task, the **Critical Technologies Book,** representing a set of technology roadmaps and technology information sheets, was established for the priority materials surface engineering technologies with the best prospects and/or of crucial importance for industry in the nearest 20 years.

Technology roadmaps, being a graphical comparative analysis tool, were established based on the results of foresight research backed up with the outcomes of traditional materials science research [11-18]. A layout of the custom technology roadmap corresponds to the first quarter of the Cartesian system of coordinates. Three time intervals for the years (2010-11, 2020, 2030) are provided on the axis of abscissa, and seven main layers were applied onto the axis of coordinates answering subsequently to more and more detailed questions: When? Why? What? How? Where? Who? How much? The main technology roadmap layers were divided into sub-layers and hierarchised starting with the top, most general layers determining all-social and economic reasons of manufacturing, ending with the bottom layers detailing organisational and technical matters concerning the place, contractor and costs. The relationships between the individual layers and sub-layers of the technology roadmap are presented with the different types of arrows representing, respectively, cause and effect relationships, capital ties, time correlations and two-directional data and/or resources flows. The technology roadmaps prepared with a custom concept are a very convenient tool for a comparative analysis enabling to select the best technology according to the criterion chosen. Besides, their undisputed advantage is flexibility and, if needed, additional sub-layers can be added or expanded for the maps according to the circumstances of the industry, size of enterprise, scale of a company's business or an entrepreneur's individual expectations. An example of a roadmap prepared for Cathodic Arc Deposition (CAD) and in Fig. 4 has been presented.

The technology roadmaps are detailed and supplemented by **technology information sheets**. They contain technical information very helpful in implementing a specific technology in the industrial practice, especially in SMEs not having the capital allowing to conduct own research. The technology information sheets provide, in particular, a description of the technological process progress and a characteristic of a physiochemical phenomenon accompanying the technological processes, the advantages and disadvantages of the relevant technology, the most prospective detailed technologies and substitute / alternative technologies. A technology information sheet also contains the types of a coating / surface layer that may be deposited or the processes occurring at the substrate surface, as well as the specific properties of coatings / surface layers / treated surfaces as a result of technological processes. A special heed was paid also to the general physiochemical conditions of technological process implementation, substrate material preparation methods, research instrument type/kind and possible specific accessories. Besides, the research results acquired with an expert research method have allowed to provide the following details in the developed sheets: the impact of technology application on the predicted and expected material properties, the efficiency of preventing the consequences of wear, industry section acc. to the PKD classification having the highest technology applicability, the applicability of computer modelling and steering methods and the development prospects of the individual analysed technologies. In addition, each technology information sheet provides a general or example diagram of the considered production process and a three-part list of the recommended references.

State-of-art PVD technologies can be extensively applied in industrial practise: in the tool, machine, electronic, automobile, aviation, optic, macro-, nano- and optoelectronic, medical, dental and plastics industry. The selected data regarding the possibilities and conditions of practical applications for the technologies analysed, representing an extract from the roadmaps created for each of 10 technology groups, is provided in Table 1.

Table 1.
The PVD practical implementation possibilities and requirements.

PVD	Product	(1)	(2)	(3)	(4)	(5)
CAD	Hard edges of cutting tools; pressure moulds and dies of injection moulders with anti-adhesive coatings; other special tools and machine parts.	5	6	9	6	7
RMS	Hard edges of cutting tools; pressure moulds; dies of injection moulders; machine parts; architectural glass; optical, electronic and micro-electronic components; LED and OLED; implants.	7	8	8	8	8
PPM	Cutting tools and edges of cutting inserts; punching and extruding tools; injection moulds; electronic parts.	4	5	4	3	4
IBAD	Special glass; LCD; semi-conductors; MEMS; glass parts coated with transparent coating and/or antireflective coating; polymeric parts; sharp edges of cutting tools; biomedical implants.	5	7	7	5	4
HHCD	Cutting tools and edges of cutting inserts; special glass; electronic components; turbine edges of aircrafts engines.	7	5	5	7	6
EB-PVD	Edges of gas turbines; parts of aircraft engines; parts of hot-work machines; cutting tools and edges of cutting tools; electro-mechanical microsystems (MEMS).	7	7	5	6	6
BARE	Metal and wood processing tools; edges of cutting tools; special glass; electronic components.	4	5	7	5	6
ICB	Electronic and microelectronic components (conductors and insulators) and optoelectronic components; metal processing tools; parts coated with organic coatings.	5	4	4	5	5
TAE	Tools with sintered carbide substrate; edges of cutting tools; bearings; optical filters; lenses; semi- and superconductors for micro- and optoelectronics.	4	2	4	5	6
PLD	Biocompatible parts, including implants for medicine and dentistry; optical filters; mirrors; lenses; nanoelements for electronics and optoelectronics; tools; cutting inserts with CBN edge.	7	6	3	4	5

LEGEND: (1) Machine park modernity; (2) Capital requirements; (3) Production size; (4) Quality and reliability; (5) Proecology

Note: Research results are presented in universal scale of relative state, where:1 is minimal and 10 is excellent level.

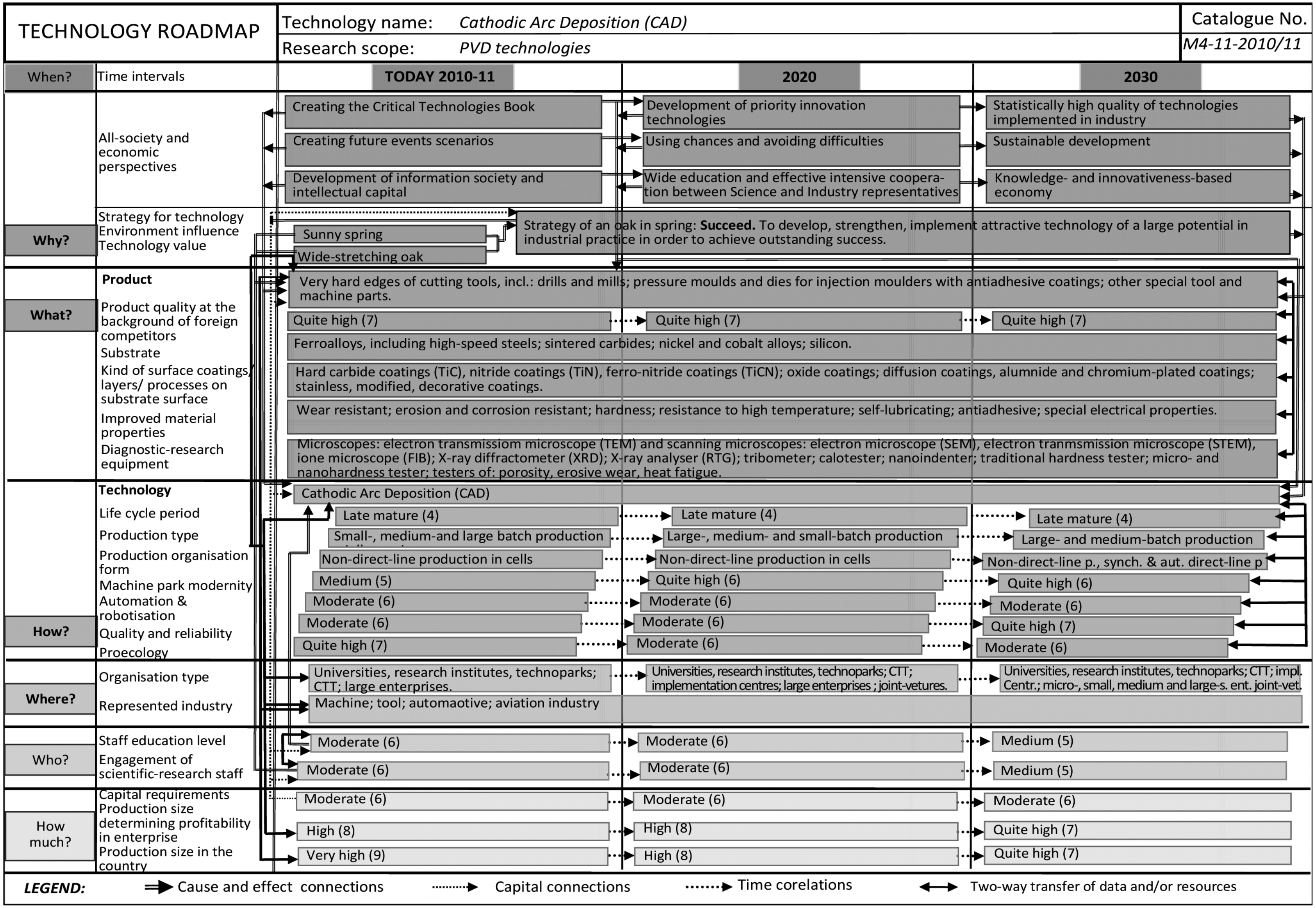

Fig. 4. An example technology roadmap prepared for Cathodic Arc Deposition (CAD)

5. Summary

The primary goal of foresight research aimed at acquiring explicit and implicit knowledge from experts is to strive for sustainable development, improved statistical quality of the technologies applied in the industry and the development of knowledge- and innovation-based economy the importance of which cannot be overestimated. All the technologies subjected to foresight research for the highly assessed thematic area "PVD technologies" have metal pairs or plasma phases crystallisation in common. They differ, however, in the usage of physical processes, placement of the zones where the pairs of a deposited material are produced and ionised, the method of producing and depositing the pairs of the metals or compounds being deposited, intensification of the layers deposition process [19] and the lifecycle phase. The factors mentioned above are decisive for the internal potential and attractiveness of the technology and intensity of environment influence, hence the possibilities of applications in various industries according to the development strategy assumed. An attempt for an objectivised assessment of 10 groups of PVD technologies in this context has been made in this article. The following matrices are used for visualising the strategic position of the specific technologies: dendrological, meteorological and strategies for technologies ones. A comparative analysis of the specific technologies is possible using technology roadmaps permitting to choose the technology best for the assumed criterion detailed out in the technology information sheets.

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