Development of a Technology Evaluation Score Model for Manufacturing Technologies

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Abstract

Leveraging new manufacturing technologies is one key element for producing firms to stay competitive. The complexity and amount of technologies as well as their influence factors (e.g. market, environment, and society) are increasing every day. Firms require tools to leverage them based on their current situation. The developed technology evaluation score model enables firms to evaluate selected manufacturing technologies on the operational technology management level in a standardized way. The model is adaptable to the requirements of the firm. It considers business, environmental and social aspects. After the evaluation, the technologies are prioritized and thereby enable a competitive advantage.

Keywords: Technology Evaluation, Manufacturing Technologies, Operational Technology Management

Introduction

Knowing the actual and applied value of manufacturing technologies is fundamental for the firm’s competitiveness thus enabling the selection of the superior technologies considering the limited R&D resources and setup of that firm. From the manufacturing perspective, the firm needs to establish production processes, prepare facilities for production ramp up, and improve manufacturing yields for profitability. Evans (2015) stated that earlier practices such as focusing on product costs, quality and time are no longer enough to ensure competitive advantages in the manufacturing industry. New technologies arise every day and firms need to be able to react fast and assess them (Teece et al., 1997). They must be evaluated, adopted and routinized in the firm (Zhu et al., 2006). While a variety of evaluation models for manufacturing technologies exist in literature (Dengler et al., 2017), most of them focus only on business aspects or selected points of the technology or they are too complex to be actually applied in the industry. Recently, researchers started to also include agile processes in these evaluation systems such as proactive management (Schönmann et al., 2016) or cycle-oriented evaluation (Dengler et al., 2017) to constantly assess the technology and thereby increase the competitive advantage of the firm. Thereby, many models concentrate on the strategic technology management level with different production outputs for demands and order winning criteria (Miltenburg, 2005). Environmental issues play a major part in strategic manufacturing decisions (Azzone and Noci, 1998; Pun et al., 2002). On the operational technology management level, the exploitation of a technology, environmental criteria are not considered in a holistic evaluation models. Furthermore, social effects, e.g. employment rate changes or other societal impacts, are lacking due to their usually reflection in the macroscopic contexts but not on the microeconomic level of a firm (Brandenburg et al., 2014). In this paper the technology evaluation score model, which has been developed by the authors, is investigated with respect to the important criteria on the operational technology management level. Beside that the model addresses the increasing complexity of manufacturing (ElMaraghy et al., 2012) and challenges in the implementation process (García et al., 2013) in a more industry-related model. García (2013) listed the investment justification process, decision and analysis process, lack of knowledge among others as main problems in the implementation of advanced technologies. We assume that the combination of strategic evaluation models as Dengler and Miltenburg with the integration of social and environmental criteria helps firms to increase competitive advantage by addressing these problems in a standardized way on the operational technology management level. In the next section we provide the theoretical background to understand the field of application and evaluation focus. Afterwards we describe the research methodology and explain the empirical findings with a sensitivity analysis as well as a use case of the developed model. The discussion and conclusion lead to the assumption, that the evaluation of technologies on the operational technology management level enables competitive advantage for the firm by standardized evaluation and prioritization of complex manufacturing technologies during their development and implementation.

Theoretical background

Operational technology management level of manufacturing technologies

Firms are facing a multitude of challenges, like justification of investment decisions, conflicting objectives, or lack of knowledge of the benefits (García et al., 2013), when choosing and implementing advanced manufacturing technologies, defined as any equipment or methodology that is part of the production system for improving performance (Chuu, 2009). Consequently, not only on the strategic level the assessment and selection of manufacturing technologies is crucial in order to assure the competitiveness of a firm (Phaal et al., 2004). The technology management consists of three level - corporate, business, and operational (Skilbeck and Cruickshank, 1997). “Corporate” is concerned with the multi business activities in respect to the world market (Perrino and Tipping, 1989). “Business” links the technological activities and market focus to ensure competitive advantages in the firm. In this area several tools were developed to manage technologies (e.g. Betz, 1993; Steel, 1989). “Operational” addresses the internal R&D and innovation management of the business (Twiss, 1992). Cetindamar (2009) defined six generic technology management activities: 1. Identification, 2. Selection, 3. Acquisition, 4. Exploitation, 5. Protection, and 6. Learning. This study focuses on the exploitation activity on the operational technology management level. The technology was internally identified, selected, and an acquisition strategy defined (Probert et. al, 2000). In the exploitation activity the desired profit or other benefits can be generated in the firm. The implementation, absorption and operation of the technology are required to lift these benefits. The production processes and manufacturing systems technologies are linked to the product context (Phaal, 2006). They are key drivers for cost reduction (Schuh et al., 2014) and process efficiency (Klocke et al., 2014) as well as product functionality improvement by enabling new product features e.g. by 3D printing of components.

Technology evaluation models

A variety of approaches and models for evaluating manufacturing technologies have so far been presented in literature (Dengler et al., 2017) on the strategic technology management level to obtain competitive advantages in the firm. Dengler (2017) highlighted that cost, quality, volume, flexibility, sustainability and product feasibility are the evaluation criteria with the highest usage frequency (Dengler et al., 2017). The systematic method of Miltenburg (2005) uses similar criteria for the evaluation of factories and international manufacturing to define a manufacturing strategy to be first in the market. His evaluation is based on the quality, delivery, cost, flexibility, innovativeness and performance criteria in regard to the product and volume. Most of the models focus on the business needs and the evaluation of the monetary value of technologies (Chan et al., 2000). The cycle-oriented evaluation model of Dengler integrates new criteria as interconnectivity due to the gain in importance of data transmission and exchange in production (Dengler et al., 2017). While this leads into the right direction, increasing complexity of manufacturing (ElMaraghy et al., 2012) also require technology evaluation models on the operational level. The integration of environmental and social aspects with economic considerations, known as the triple-bottom-line dimensions of organizational sustainability (Elkington, 1998, 2004), has continuously gained relevance for managerial decision-making in general and operations management (Kleindorfer et al., 2005). The employee involvement is an essential component in the decision-making and financial success of the firm (Rao, et. al 1999). Holistic models are established in the sustainable supply chain management (Brandenburg et al., 2014). In this study we adopt these factors onto the operational technology management of manufacturing technologies to address the problems in the implementation process of manufacturing technologies.

Research method

The research is a deductive approach to prove the assumption to increase the competitive advantage of firms by evaluating technologies on the operational technology management level. The model was developed and applied in a manufacturing plant of the Siemens AG. Beside the listed criteria of Dengler and Miltenburg, the model incorporates the innovation scorecard (Little, 2001), monetary value approaches like cost utility analysis, net present value, return on investment, and payback period (Chan et al., 2000) and further important criteria of the triple-bottom-line. All approaches were combined to evaluate the overall technology impact on the manufacturing. A sensitivity analysis was executed in the model-building phase to identify irrelevant model inputs (Felli and Hazen, 2004) and to demonstrate to potential users the validity of the results of the model (Gass, 1983) before the utilization. Sensitivity analysis is nothing but the process of checking the robustness of the obtained output. To establish the sensitivity, the model was 2000 times used with randomly generated weightings and ratings for one technology. Afterwards, the model has been applied together with project managers on eighteen different manufacturing technology projects. Furthermore, the model has been discussed and reviewed with various shop floors responsible. The management contributed and agreed on the weightings of the criteria. Herewith, research data was collected, and the model was validated with direct feedback for improvements.

Empirical findings

The outcome of the model is a technology evaluation score (TES). It includes weighted main criteria of economic efficiency, quality, product functional capability, environmental health and safety, strategy, resource input, and social aspects. The partial scores of the main criteria result from the monetary approaches for the economic efficiency and multiple questions for non-monetary criteria, which are answered by technology experts and project stakeholders and summarized afterwards.

Technology evaluation score model description

The model is used for efficient technology decisions on the operational level. The decision is generated by determine a TES based on 7 factors. This evaluation is executed for all considered technologies. The technology development and implementation are executed for those technologies, which achieve a certain limit e.g. at least a minimum score of 50 %. Other criteria like assigning a certain amount of R&D budget are also possible. Figure 1 illustrates the TES model.

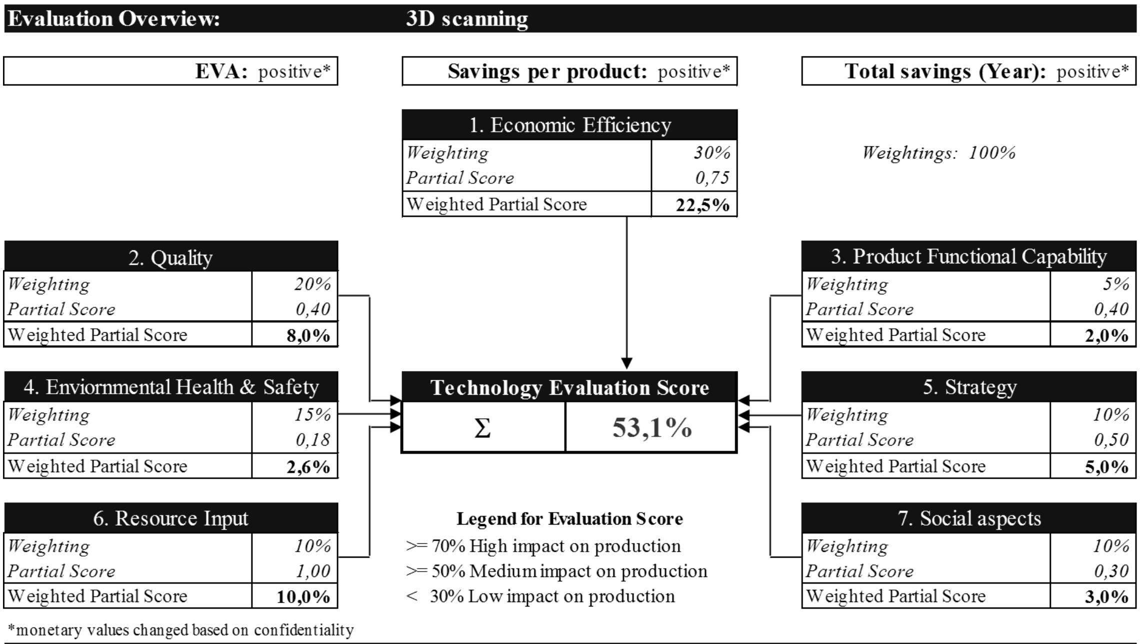

Figure 1 – Technology Evaluation Score Model - Overview

The TES is calculated with the following formula:

$$\text{TES} = \sum_{i=1;\,k=1}^{N} \Sigma(WSC_i \; x \; RSC_i) \; x \; WC_k$$

TES: Technology evaluation score; WC: Weighting of main criteria; PSC = $\Sigma(WSC_i$ x $RSC_i)$: Partial score of main criteria; WSC: Weighting sub criteria; RSC: Rating sub criteria

The economic efficiency score is based on the cost saving per product, amortization, return of investment and economic added value. To define the cost savings, a comparison of the old and new manufacturing process is executed. All manufacturing costs per part are considered in the comparison (e.g. material, machine and labour cost etc.) (Schuh, 2012; Reinhart, 2011). Additionally, quality non-conformance costs are included as well as one-off effect cost savings (e.g. scrap value). The amortization, return of investment and economic added value are calculated with the capital expenditures, abbreviations, R&D costs linked to the cost savings and the production load (Koho, 2010). The outcome of the calculation is considered as part of the utility analysis, which is used for the other criteria. In the utility analysis, the operational stakeholder rate four questions in concern of their fulfilment level in a given scale. Each of the four questions is weighted by the management before to adapt the model onto the firm requirements. The fulfilment level is multiplied with the question weighting. All partial scores are summarized to define the partial score of the main criteria (e.g. quality - 0.4). The quality comprises the improvement of the production quality (accuracy, durability, first-pass-yield etc.) (Koho, 2010), reduction of the reject rate, acceleration of quality notification solving, and definition of corrective and preventive actions of the production. The product functional capability includes questions concerning individual product functional improvements, reduction of the life cycle cost, and improvement of the reliability, availability, maintainability, durability and safety of the product (Reinhart, 2011). The environmental, health and safety (EHS) criteria describe environmental factors (less production resources and tools, less waste etc.) (Stauder, 2016), improvement of work safety (physical integrity, injuries, and health burdens), work simplification, and workload balance. The strategy contains relevant questions about the intellectual property, patent, support of existing and general firm strategy, and the strategic network (suppliers, customers, partners etc.). The resource inputs comprise the effort for implementation, available knowledge and capacities (machine, labour, hardware, software etc.), and possibility to transfer the technology. The social aspects contemplate the employee training of new work skills, worker empowerment, career development of the technology operator, and overall social influence of the technology.

Sensitivity analysis of the technology evaluation score model

The target of the sensitivity analysis is to assess the impact of the weighting factors as well as the partial scores, as the weighting factors are chosen by expert judgement in general to rate different technologies and for the partial scores by experts for individual technologies. The sensitivity analysis was executed with the "3D scanning" technology to validate the influence of the partial scores in combination with the weighting of the criteria on the TES. To establish the sensitivity, the model was used 2000 times via randomly created weightings and ratings for the technology. Figure 2 shows the distribution of the impact factors in the 2000 evaluation.

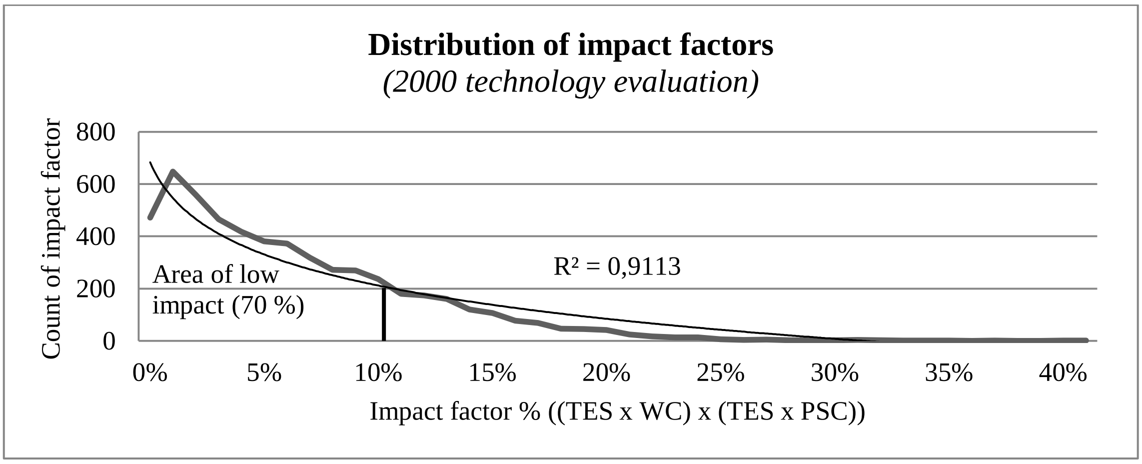

Figure 2 – Distribution of impact factors on TES – Weighting and partial scores

According to the sensitivity analysis, changing the weight and the partial score of the criteria alters the decision for or against a technology. Considering another weighting of a criterion or rate a criterion differently results in a shift of the TES. We calculated the impact factor by multiplying the influence of each weighted main criteria on the TES with the influence of the partial score of each main criterion on the TES. Taking the 2000 randomly created evaluation into account, most weightings in combination with the ratings have no influence on the TES. More than 70 % of the combinations are below the impact factor of 10%. The logarithmic coefficient of determination (R^2) of 0.9113 indicates that the rate of the impact is constantly dropping and then stays constant. Anyhow, the decision-making process is sensitive to the type of criteria, the number of participants involved, and their expertise with the subject, their selection should be carefully done. The data reveals that the model is consistent.

To further validate the model and analyse the data, we executed the second part of the sensitivity analysis by taking a detailed view on the TES of the evaluations. The figure 3 demonstrates the range of TES within randomly generated 2000 evaluation thus the 3D scanning technology could achieve TES values between 20 and 80 % but considering only the 80% close to the average value the range is between 40 and 60 % taking into account that the TES is featuring a normal distribution.

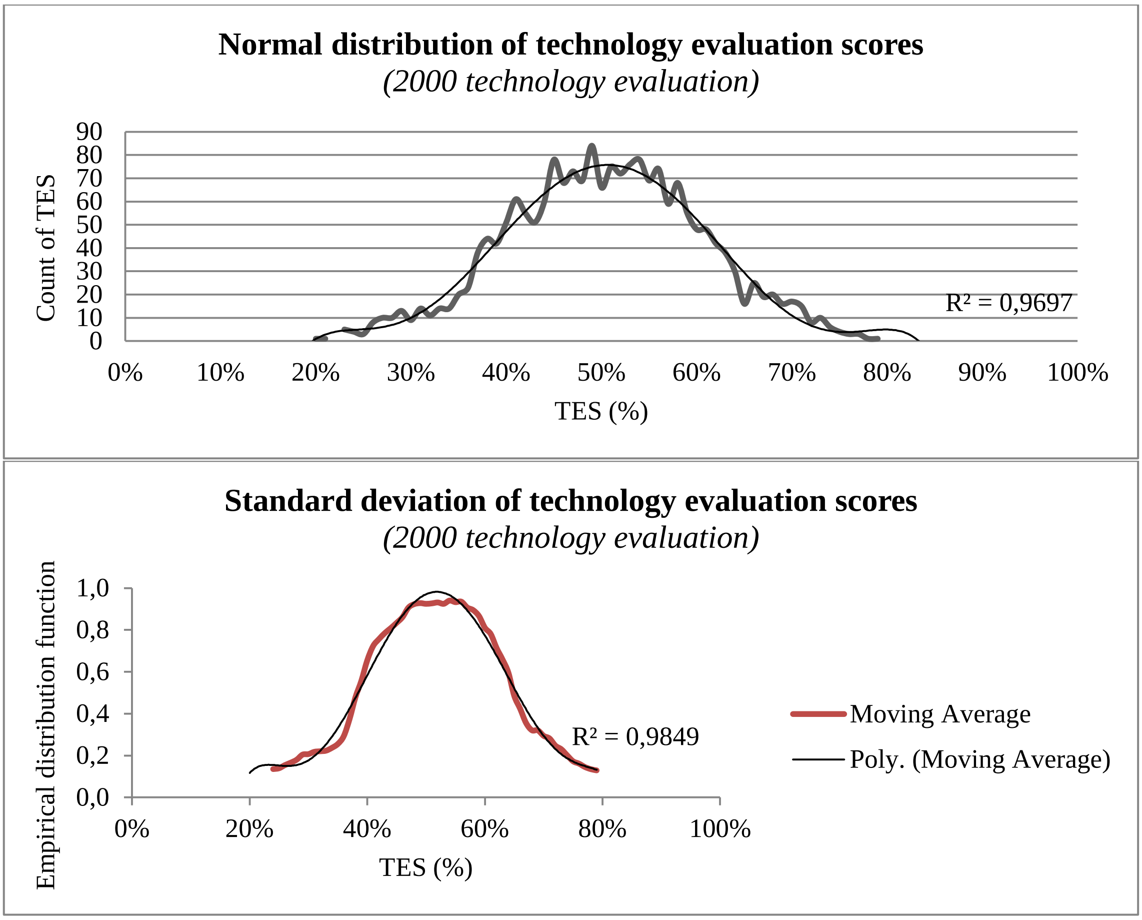

Figure 3 - Normal distribution (upper) and standard deviation (lower)

The added polynomial trend line is used for fluctuating data. The sixth grade polynomial coefficient of determination of 0.9697 and 0.9849 shows a high consistency of the line with the data in both diagrams. Firstly, we counted the distribution of TES over the 2000 evaluation. This data already revealed that the model generates consistent distributed scores. Each of the evaluated technologies has been pre-selected in the firm, so that none of these technologies should reach a score of zero percentage. Due to the complexity in technologies none of the considered technologies can reach a score of hundred percentages of all evaluated criteria. For example, one technology supports environmental criteria, but such technology is not that cost efficient. A second technology might support the digitalization in the firm but has a bad influence on the social aspects. This complexity is integrated in the developed model.

The standard deviation σ of the moving average of the fluctuating data is 75.4 %. The area of σ is between a TES of 37 % and 64 %. This reveals that the model generates consistent scores, which differentiate enough to prioritize and thus budget that technology development in the firm. Thereby, the weightings and ratings of the different criteria has mostly no high impact on the TES. The model is validated via a sensitivity analysis and can be further validated in their applications. Technologies with a score over 70 % are outside the standard deviation and should be prioritize based on their high impact on the production of the firm.

Multiple-project application of the model

A TES comparison of all technologies in the exploitation activity on the operational technology management is shown for one plant of the Siemens AG in Figure 4. The comparison illustrates the final TES at a given time. Each evaluated technology has a specific TES.

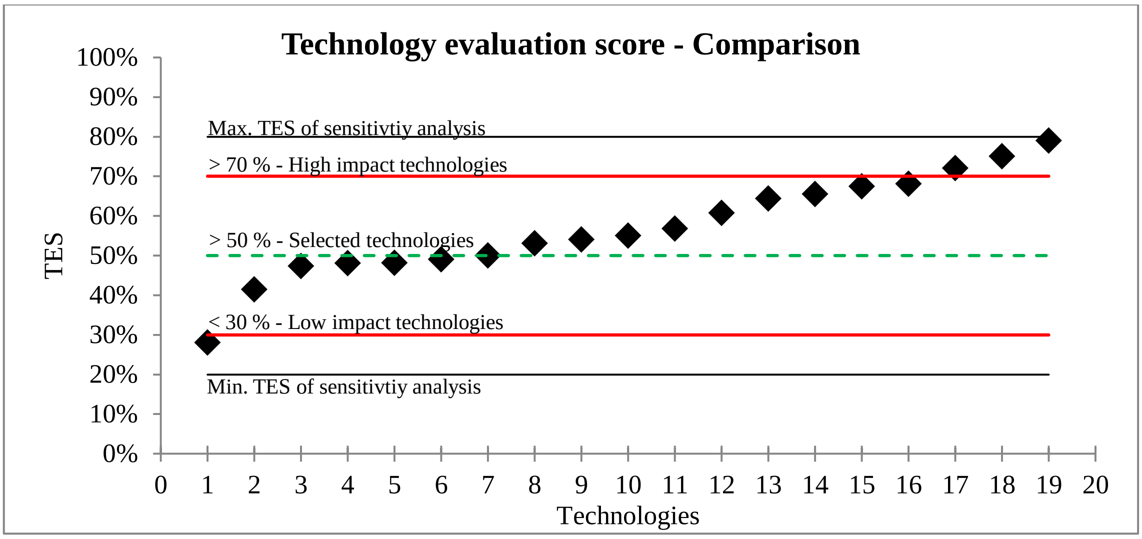

Figure 4 – Technology evaluation score - Comparison

In the first application of the model technologies with an evaluation score over 70 % are defined as technologies with a high impact on production. This score is selected based on the standard deviation of the sensitivity analysis and by the management. The data shows that three of the evaluated technologies reach this score. In this case all technologies with a TES over 50 % were selected for further development and implementation in the plant. Only one evaluated technology ranges under the 30 % and is a technology with a low impact on production. The consideration of the model in their daily business and frequent technology planning enables the firm to quickly get an overview of the technologies in development and implementation.

If the management wants to implement technologies with a strategic focus to improve e.g. EHS in the plant, the partial score of EHS could be plotted and technologies with high ratings in EHS could be prioritized. Figure 5 reveals a comparison of the TES and one partial score of a main criterion of the technologies.

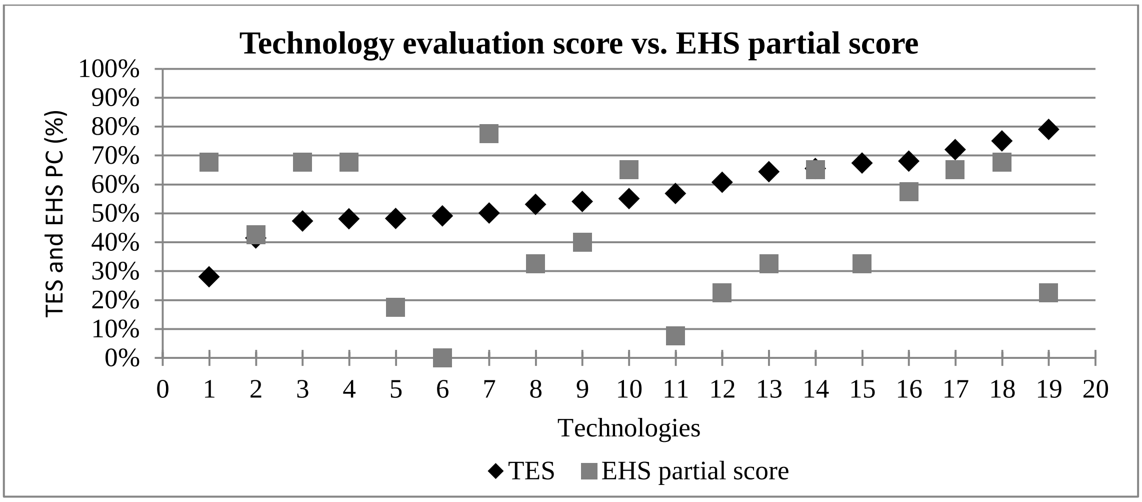

Figure 5 – Technology evaluation score vs. EHS partial score

The values demonstrate that some technologies are scored as medium impact technologies with a high impact on the EHS. The utilization of the model enables the firm to overview various technology criteria. The firm can constantly align their technology exploitation based on their internal needs. The model allows an internal customization of the criteria. It helps to constantly manage the technology projects and adapt it regarding the firms need as well as to react on market changes and governmental regulation, and thereby generate a competitive advantage for the firm. To leverage these advantages, the R&D expenses have to be connected with the evaluation outputs in the firm.

Discussion and conclusion

Theoretical implications

The present study makes two important theoretical contributions. The model was developed by using criteria of the product cycle-oriented evaluation of manufacturing technologies and the manufacturing outputs criteria depending of the product and volume linked with existing operative models in the firm. It addresses the need of industry-related models on the operational level of technology management (Skilbeck and Cruickshank, 1997) to increase competitive advantages. The model allows evaluating strategically selected technologies in their application of an individual production environment. It provides insight for the development and implementation of the technology in a manufacturing perspective and supports the decision-maker in the firm. The sensitivity analysis supports the applicability of the model in the industry. The model is valid and generates consistent data for decision maker. Thereby, the impact of the weighting and rating is only crucial in a limited amount of evaluation. The decision-making process with the model is sensitive to the expertise with the subject of the participants as well as the expertise with the model.

The second contribution of the present study is the consideration of social and environmental criteria to access the technology on the microeconomic level. Thereby, a more comprehensive approach of influence factors is used in the evaluation score of the technologies. This creates a bigger picture as well as new shifts in the importance of manufacturing technologies. So far non-considered technologies have the possibility to arise in the application field of the firm. This clearly depends on the market situation and the manufacturing environment.

The problems in the investment justification process, decision and analysis process, and knowledge management (García, 2013) during the implementation of manufacturing technologies is clearly supported by the standardized and aligned model within the production and management. Complex manufacturing technologies are connected with influencing criteria to enable the competitive advantage of the firm.

Managerial implications

The evaluation score model was developed with employees, management, customers and users. Through iterative testing, it could be immediately applied in the industrial setting. The comparison of the individual projects with the technology evaluation scores enabled the firm to internally prioritize and budget the manufacturing technologies. The standardized procedure ensured a common understanding of each impacting factor in the plant and drastically improved the cooperation between management, project managers and the shop floor. On the monetary side, business figures can be shown including the direct impact on the product cost. Non-direct monetary factors (e.g. workplace safety) have also been included and hence enhance the importance of some technologies that might not be considered relevant when only looking at the business side. The model supports the decision-making process based on quantitative figures in the firm.

Limitations and future research

The evaluation model has been developed based on a one case scenario. Adopting the model to a multiple case study design in other manufacturing context would provide the potential for cross-case analysis, which is not possible at present. The sensitivity of the criteria was not discussed across different technologies. Further investigations must identify the validation of the criteria across different technology projects. A literature review of social and environmental factors in the manufacturing perspective would help to identify main clusters to create a more generic and transferable evaluation model.

References

Azzone, G. and Noci, G., (1998). Identifying effective PMSs for the deployment of “green” manufacturing strategies, *International Journal of Operations & Production Management*, Vol. 18, Nr. 4, pp. 308-335.

Betz, F. (1993). Strategic Technology Management, McGraw-Hill, New York.

Brandenburg, M., Govindan, K., Sarkis, J., Seuring, S. (2014). Quantitative models for sustainable supply chain management: Developments and directions, *European Journal of Operational Research*, Vol. 233, pp. 299–312.

Cetindamar, D., Phaal, R., Farrukh, C. J.P. (2009). Understanding technology management as a dynamic capability: A framework for technology management activities, *Technovation*, Vol. 29, pp. 237–246.

Chan, F. T. S., Chan, M. H., Tang, N. K. H. (2000), “Evaluation methodologies for technology selection”, *Journal of Materials Processing Technology*, Vol. 107, No. 1-3, pp. 330-337.

Chuu, S.J. (2009), “Selecting the advanced manufacturing technology using fuzzy multiple attributes group decision making with multiple fuzzy information”, *Computers & Industrial Engineering*, Vol. 57, pp. 1033-1042.

Dengler, C., Schönmann, A., Lohmann, B., Reinhart, G. (2017), “Cycle-oriented Evaluation of Production Technologies: Extending the Model of the Production Cycle”, *Procedia CIRP 52*, pp. 198-203.

Elkington, J. (1998). Cannibals with forks: The triple bottom line of the 21st century. Stoney Creek/CT: New Society.

Elkington, J. (2004). Enter the triple bottom line. In A. Henriques & J. Richardson (Eds.), The triple bottom line: Does it all add up? (pp 1–16). London: Earthscan.

ElMaraghy W., ElMaraghy H., Tomiyama T., Monostori L. (2012), “Complexity in engineering design and manufacturing”, *CIRP Annals. Manufacturing Technology,* Vol. 61, No. 2, pp.793-814.
Evans, R.D., Gao, J.X., Mahdikhah, S., Messaadia, M. and Baudry, D. (2015). A review of crowdsourcing literature related to the manufacturing industry, *Journal of Advanced Management Science*, Vol. 4, Nr. 3, pp. 224-321.
Felli, J. and Hazen, G. (2004). Javelin Diagrams: A Graphical Tool for Probabilistic Sensitivity Analysis, *Decision Analysis*, Vol. 1 No. (2), pp. 93–107.
Gass, S. I. (1983). Decision-Aiding Models: Validation, Assessment, and Related Issues for Policy Analysis, *Operations Research*, Vol. 31 No. 4, pp. 603–631.
García A, J.L. and Alvarado I, A. (2013), “Problems in the implementation process of advanced manufacturing technologies”, *International Journal of Advanced Manufacturing Technology*, Vol. 64, No. 1-4, pp. 123-131.
Koho, M., (2010). Production System Assessment and Improvement: A Tool for Make-to-Order and Assemble-to-Order Companies, *Tampere University of Technology*, Tampere.
Klocke, F., Buchholz, S., Stauder, J., (2014). “Technology chain optimization: a systematic approach considering the manufacturing history”, Production Engineering, Vol. 8, No. 5, pp. 669-678.
Kleindorfer, P. A., Singhal, K., & van Wassenhove, L. N. (2005). Sustainable operations management, *Production and Operations Management*, Vol. 14, Nr. 4, pp. 482–492.
Miltenburg, J. (2005). Manufacturing Strategy - How to Formulate and Implement a Winning Plan, *Productivity Press*, New York.
Little, A.D. and European Business School (2001), Steigerung des Unternehmenswertes durch Innovationsmanagement, *Gabler Praxis*, Wiesbaden.
Perrino, A.C. and Tipping, J.W. (1989). Global Technology Management, *Research Technology Management,* Vol. 32, Nr. 3, pp. 12-19.
Phaal, R., Farrukh, C. J. P., Probert, D. R. (2004), “A framework for supporting the management of technological knowledge", *International Journal of Technology Management*, Vol. 27, No. 1, pp. 1-15.
Phaal, R., Farrukh, C. J.P., Probert, D.R. (2006). Technology management tools: concept, development and application, *Technovation,* Vol. 26, pp. 336-344.
Probert, D.R., Phaal, R., Farrukh, C. J.P. (2000). Development of a structured approach to assessing technology management practice, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, pp. 313-321.
Pun, K.F., Hui, I.K., Lau, H.C.W., Law, H.W., Lewis, W.G., 2002. Development of an EMS planning framework for environmental management practices. *International Journal of Quality & Reliability Management*, Vol. 19, Nr. 6, pp. 688-709.
Rao, S.S., Solís, E.L. and Raghunathan, T.S. (1999). A framework for international quality management research: Development and validation of a measurement instrument, *Total Quality Management,* Vol. 10, Nr. 7, pp. 1047-1075.
Reinhart, G., Schindler, S., Krebs, P., (2011). Strategic Evaluation of Manufacturing Technologies, in: Hesselbach, J., Herrmann, C. (Eds.), Globalized solutions for sustainability in manufacturing. *Proceedings of the 18th CIRP International Conference on Life Cycle Engineering,* Springer, pp. 179–184.
Schönmann, A., Greitemann, J., Reinhart, G. (2016), “Proactive Management of Production Technologies: A Conceptual Framework”, *Procedia CIRP 52*, pp. 198-203.
Schuh, G., Graw, M., Schön, N. (2014), “Exploitation-oriented Manufacturing Technology Development”, *Procedia CIRP 17*, pp. 680-685.
Schuh, G., Schubert, J., Wellensiek, M., (2012). “Model for the Valuation of a Technology Established in a Manufacturing System”, *Procedia CIRP 3*, pp. 602–607.
Skilbeck, J.N. and Crucikshank, C. M. (1997). A framework for evaluating technology management process, *Portland International Conference on Management and Technology*, Portland, July.
Stauder, J., Buchholz, S., Mattfeld, P., Rey, J., (2016). Evaluating the substitution risk of production systems in volatile environments. *Production Engineering Research and Development*, Vol. 10, Nr. 3, 305–318.
Steele, L.W. (1989). Managing Technology – The Strategic View, McGraw-Hill.
Teece, D. J., Pisano, G. and Shuen, A. (1997). Dynamic capabilities and strategic management, *Strategic Management Journal*, Vol. 18, Nr. 7, pp. 509-533.
Twiss, B., (1992). Managing Technological Innovation, 4th ed., Pitman Publishing, London.
Zhu, K., Kraemer, K.L. and Xu, S. (2006). The process of innovation assimilation by firms in different countries: a technology diffusion perspective on E-business, *Management Science*, Vol. 52, Nr. 10, pp. 1557-1576.