Review of innovation theories in the perspective of Bayesian decision analysis

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ABSTRACT: Technological innovation will only impact if it creates significant technological, industrial and societal benefits. In this perspective, this paper contains an outline of innovation theoretical developments and innovation economic and social theories in the perspective of Bayesian decision analyses. Based on these outlines, approaches of how innovation and technology development can be aligned with and supported by Bayesian decision analyses are described. For technology readiness support, three distinct decision analysis types for different technology readiness levels are summarized. For the value forecasting decision analysis, the further development of the perfect information approach is highlighted. The conclusions contain identified, joint innovation and decision theoretical aspects for targeted decision value analyses formulation to support innovation and its scaling.

1. INTRODUCTION

Innovation plays a crucial role in shaping the progress of technology, industry, economy and society. Never before, the need for sustainability-based industrial innovations has been as urgent as today (see e.g., Hazarika and Zhang (2019), Chistov, Aramburu et al. (2021)).

In engineering, innovation is traditionally focused on technology readiness development. Technology Readiness Levels (TRL) have been established in high technology sectors such as space engineering (e.g., in the US National Aeronautics and Space Administration NASA and the European Space Agency ESA, see e.g. Sadin, Povinelli et al. (1989)) and also serve as guidance to the European Union research and innovation frameworks such as Horizon Europe and the programs of the European Innovation Council, see e.g. Héder (2017). The European Innovation Council (eic.ec.europa.eu) is focused on the industrial scaling of innovation and technological aspects of innovation.

The technology readiness development can be supported by decision value analyses, i.e., with decision analyses on the basis of Bayesian decision theory and utility theory (Thöns, Irman et al. (2021)). This support will facilitate to guide the technological development in a very early stage and in later stages to optimize the performance of the technology for industrial and societal benefit generation, i.e., an innovation scaling.

In an economic context, innovation originates from the competition of indebted producers for purchase contracts. The purchase contracts for the produced goods are required to pay the sum of interest and redemption from the debt contract needed for the investments for good production. The investment can be financed by a debt contract and interest on property, which constitutes the fundamental characteristic of the industrial period (Heinsohn and Steiger (2010)).

The technological service life of the product and production technologies is reached by wear and tear. However, the economic service life is determined by technological progress, i.e., innovation, which may lead to an economic devaluation of the current technology. With such a devaluation, a competitor may outperform other indebted competitors for product purchase contracts (Heinsohn and Steiger (2010)). It is apparent that there are disruptive industrial-societal implications in such processes.

The outlined aspects of innovation, namely (i) the technology readiness development, (ii) its support by decision analyses, and (iii) the economic characteristics outreaching to societal impacts are seldomly jointly addressed.

This paper contains an outline of innovation theoretical developments and theories (Section 2), namely disruptive innovation theory by Christensen for describing the economic implications, and the innovation diffusion theory representative for the social innovation implications. Together with a summary of decision value analyses (Section 3), the decision analysis utilization for innovation support is outlined. Here, the importance of a further development and alignment of the perfect information approach by Raiffa and Schlaifer (1961) is highlighted. Section 4 contains a summary of decision analysis types to support the technology readiness development on three distinct stages. The conclusions (Section 5) contain the identification of innovation theoretical aspects for targeted decision value analyses formulation.

2. OUTLINE OF INNOVATION THEORIES

Innovation refers to the creation of new or significantly improved (i) products, (ii) processes, (iii) marketing and (iv) organization that add value to markets, governments and society (see e.g., European Commission (2013)). Moreover, innovation is a process that has, as a starting point, an idea, invention, or an opportunity (generating ideas) through which a product, service or business model is developed (implementation) and validated/commercialized by the market (dissemination). After that, there is a monitoring phase to assess the market behavior, which itself may lead to new ideas, opportunities (strategic thinking) and therefore, a potentially new innovation cycle (e.g., Dantas and Moreira (2011).

Early works, on innovation theories, can be found e.g. in Abernathy and Clark (1985), who allocated four main innovation types to the production technology and the market and costumer linkages dimensions, namely: (i) architectural, (ii) market niche, (iii) regular and (iv) revolutionary innovation (Figure 1):

- *Architectural innovation* that starts out from new technology and opens new linkages to markets and users. It defines the future basic configuration, i.e., the architecture, of product and processes and establishes the technical and marketing agenda that will guide the subsequent development.
- *Innovation in the market niche* that opens new market opportunities using existing technology, by conserving and strengthening established designs related to the production and technical systems.
- *Regular innovation* that has a significant influence on existing markets and costumers due to cumulative effects on product cost and performance by building upon established technical and production competence.

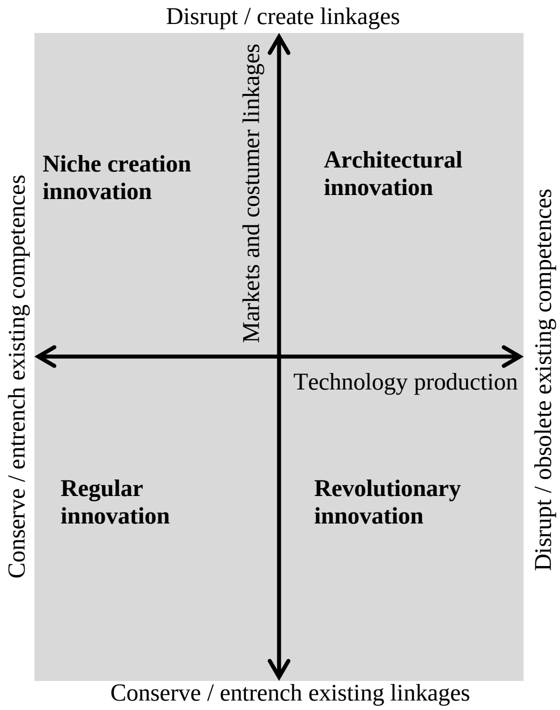

Figure 1: Innovation dimensions – technology and market (Abernathy and Clark (1985)).

- *Revolutionary innovation* in existing markets and costumers that makes established technical and production competence obsolete.

Two of the most prominent innovation theories are (i) disruptive innovation theory (e.g. Bower and Christensen (1995), Christensen, Raynor et al. (2015), Christensen, McDonald et al. (2018), Christensen (1997), Wu, Wang et al. (2019)) and (ii) innovation diffusion theory (e.g. Rogers (2003), Sood and Tellis (2005)). Disruptive Innovation is an empirically developed economic theory describing the industrial environment and technology characteristics leading to a disruption of an established market and its industries. Innovation diffusion theory describes the innovation spread as a sociological theory taking basis in time, communication and the social system and innovation adoption consequences such as social impacts for individuals, companies, industry, and society.

2.1. Disruptive innovation

Disruptive Innovation theory has been developed empirically based on observations in the disk drive industry followed by using the theory for *ex-ante* innovation outcomes in different industries (e.g. by Christensen, Anthony et al. (2004)). *Ex-ante* means predicted and refers to a macroeconomic terminology for monetary equilibrium calculations building upon 'prospective' and 'retrospective' values in regard to the savings-investment relation developed by the Stockholm School in the 1930s (Palander (1941), Steiger (2018)). Disruptive theory has also been used for informing innovation strategies (for e.g. Amazon's Kindle business, see Stone (2013)).

Disruptive innovation is characterized by four main characteristics of the baseline technological and market situation (Christensen, McDonald et al. (2018), see Figure 2):

1) Unbalanced level of customer satisfaction

The development pace of an existing technology, which outperforms the overall customer requirements for higher-performing technologies and thus, leading to an unbalanced level of satisfaction, i.e., by satisfying the needs of the most profitable costumers rather than the mainstream costumers.

2) Sustained innovation in established industry

Innovation in established companies is focused on sustained innovations, which is usually aligned with established production processes and what the market historically valued.

3) Constrained innovations

Existing customers and established profit models constrain other than sustained innovation including potentially large investments in disruptive innovation.

4) New technology development

New and commonly not yet well understood technologies emerge. These technologies may have not yet the market performance (profit) of the existing technology but address more the mainstream costumers and market requirements.

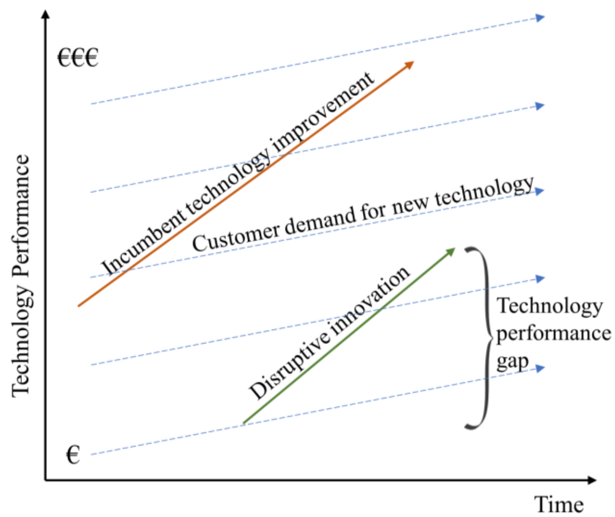

Figure 2: Disruptive innovation characterization following Christensen, McDonald et al. (2018)

In such a technological and market situation, both the new technology performance and its business model may develop and may cause a disruptive innovation. This may lead consecutively to the creation of a new market and value network with a negative impact on the market of the existing industry.

Innovative disruption may be seen also as a process over time, as time horizons may vary largely depending on the industry type and sector. As illustrative examples may serve an innovative app development for a mobile device with a short innovation period, as opposed to the just happened disruption by messenger ribonucleic acid (mRNA) vaccine development relying on decades of research and investments (e.g. Maruggi, Zhang et al. (2019)).

Future research on disruptive innovation theory has been investigated, e.g. in Christensen, McDonald et al. (2018), based on a set of studies related to disruptive innovation theory from 1970 to 2016. Future research is seen in response strategies, the temporal innovation development modelling and in joint business and technology performance models:

- *Response strategies* are to be developed to threatening disruptive innovations such as, e.g., to delay disruption by aggressively investing in existing production facilities and by co-opting new disruptive market entrants.
- *Temporal innovation development modelling* should target the explanation for the rapidness of a disruption. I.e., temporal models for the economic performance trajectories of costumer demands and technology development should be further developed.
- *Metrics as enablers of disruption* should be formulated. Here, joint business and technology performance models should be developed, which are independent of existing industry's business models - as facilitators of disruptive innovation. These metrics should allow to (a) properly differentiate between socio-cognitive based - and thus a varying and biased process (see Garud and Ahlstrom (1997)) - and an objective assessment of technology value and (b) properly account for innovation profit projections also in the long term.

2.2. Innovation Diffusion Theory

In the context of innovation, diffusion may be defined as the process by which an innovation is communicated over time among the members of a social system, see Rogers (2003). Communication here is defined as a process that relates to new ideas that are promoted by participants that share information towards a mutual consensus and definitions. In other words, communication as a two-way process of convergence, rather than as a one-way, linear act in which one individual seeks to transfer a message to another (Rogers and Kincaid (1981)).

From the society perspective, innovation diffusion is a social change, defined as the process by which alteration occurs in the structure and function of a social system. In the presence of new ideas, these may diffuse and be adopted or rejected by the society that consequently may lead to some type of social changes. The diffusion of new ideas may take place as planned or spontaneous communication forms, mainly by:

- *Centralized diffusion systems*, where a kind of protocol exists on decisions regarding when to begin diffusing an innovation, who should evaluate it, and through what channels it will be diffused. These are made by a small number of people inside of a company.

- *Decentralized diffusion systems*, where decisions are openly shared by means of the horizontal networks among the clients that are the main mechanism through which innovations spread. Ultimately, the new ideas may grow out of the practical experience of certain individuals in the client system, rather than coming from formal research and development activities (Rogers and Kincaid (1981)).

Interestingly, although initially assumed that relatively centralized diffusion systems were essential in the diffusion process of innovation, it has been found that under certain conditions several relatively decentralized diffusion systems represent an appropriate alternative to centralized diffusion.

2.3. Summary

The review of the disruptive and the diffusion innovation theories leads to the following observations:

- Implicit in the creation of a new market by a disruptive innovation is a value creation for industrial entities, individuals, and society.
- The technical product performance and its business model are important premises – beside technological development and market situation (Section 2.1) - for a disruptive innovation.
- The objective assessment of the technology in terms of profit and value generation constitutes a potential direction for future research in Disruptive Innovation theory.
- The prediction (*ex-ante*) of innovation outcomes has guided large scale disruptive innovations.
- The innovation diffusion theory is focused on social system communicative interaction and the societal role of innovations.

3. DECISION VALUE ANALYSES

Decision analyses have been formulated in an economic and management science context by Raiffa and Schlaifer (1961). Benjamin and Cornell (1970) introduced decision analysis to built environment engineering. The fundamental thoughts here are that the “states of nature” can be associated to engineering system states and that the utilities can be modeled with a monetarized consequence model. In this way, probabilistic engineering models can be used to calculate engineering system states probabilities leading in conjunction with the consequences model to a risk quantification. Built environment functionality modelling may complement the utility model. Both, the system state and the utility models, facilitate that technological decisions can be analyzed and optimized in an (macro-)economic environment.

Decision analyses are formulated with a system state X_l model, the associated utility u model, i information acquirement strategies i_i and the k actions a_k . Decision analyses are solved with the objective function (1) maximizing the expected value of the utility in regard to the j information outcomes $Z_{i,j}$ and the updated l system states including the information and action costs, $c(\dots)$.

$$U = \max_{i_i} E_{Z_{i,j}} \left[\max_{a_k} E_{X_l|Z_{i,j}} [u(a_k, X_l) + c(a_k)] \right] + c(i_i) \quad (1)$$

The objective function can be adjusted to a specific decision scenario and analysis type by omission of the respective variables and/or operators.

A decision value quantification is defined as the difference between the maximized and expected utilities of two decision analyses. The decision value is related to the difference in decision variables in the two decision analyses (see Thöns and Kapoor (2019)). Further studies, details and applications can be found in the scientific literature, see Zhang, Lu et al. (2021) for an overview.

4. DECISION VALUE ANALYSES FOR TECHNOLOGY READINESS DEVELOPMENT SUPPORT

System performance, decision and decision value analyses (Table 1) may be related to different stages of technology development (Table 2), see also the Introduction (Section 1).

In early stages of technology development (TRL 1 to 4; Table 2), technology utilization scenarios may be developed encompassing a business model and a technical system state model, which facilitates a probability-weighted cost-benefit-consequences analysis, i.e., a system performance analysis. The system performance analysis may then be adapted by information and actions, which are generically modelled. An analysis of these scenarios may reveal technology and business model performance parameters and boundaries and may forecast the potentials of the technology in comparison to the conventional technology. This approach is termed a value forecasting approach (Table 1).

Table 1: Decision value analysis types

Value forecasting: ▪ Utility and system state base scenario with conventional technology, ▪ Utility and system state scenario with new technology, ▪ Technology and market performance value projection.
Value analysis: ▪ Probabilistic technology modelling, ▪ Identification of boundaries and optimal technology and market performance parameters, ▪ Stakeholder value set quantification.
Technology value quantification: ▪ Optimization of technology value in operational technology and market environment.

The decision value forecasting approach is a further development of the perfect information approach as described by Raiffa and Schlaifer (1961). The further development regards the modelling of and analysis with full information properties namely type, precision and cost without specific models for information acquirement (see e.g., Thöns (2020)) in contrast to e.g., the infinite precision assumption.

Table 2: Technology readiness development with support of different types of decision value analyses

Technology and research screening with **value forecasting** for: TRL 1 – Basic principles observed TRL 2 – Technology concept formulated Proof and of validation of performance requirements of **value forecasts** with: TRL 3 – Experimental proof of concept TRL 4 – Technology validated in lab
Determination and optimization of technology performance parameters with a **value analysis**: TRL 5 – Technology validated in relevant environment TRL 6 – Technology demonstrated in relevant environment
Technology employment optimization with **technology value quantification**: TRL 7 – System prototype demonstration in operational environment TRL 8 – System complete and qualified TRL 9 – Actual system proven in operational environment.

Currently, the value forecasting approach is extended towards multi-component systems and towards analyses over periods of time, see Costa, Thöns et al. (2023b) and Costa, Thöns et al. (2023a). These value forecasting analyses facilitate that value-optimal integrity management strategies for an infrastructure system over the service life can be identified without specific integrity management technology modelling. The integrity management strategy identification includes the prediction of the expected utility enhancement, i.e., the potential stakeholder value set, by the integrity management.

In stages of the technology development, where laboratory performance of the technology is known more specific and detailed (TRL 5 and 6; Table 2), probabilistic technology performance models may be developed. These facilitate value analyses (Table 1) and specific technology and market performance parameters determination.

The most sophisticated decision scenario modelling and model basis may be introduced with the technology in an operational environment (TRL 7 to 9; Table 2). Here, the technology value quantification (Table 1) contains (1) the stakeholder value set to be utilized e.g., for marketing purposes, and (2) the operational technology and business model performance parameters. The technology value quantification can be related to and embedded in a code and regulatory environment and used for further product and value optimization.

5. SUMMARY AND CONCLUSIONS

This paper contains a review of innovation theories with particular emphasis on (i) disruptive innovation theory and (ii) innovation diffusion theory and in perspective of decision value analyses. Disruptive innovation theory points to integral technology and value creation performance assessment and forecasting (as a direction of future research), whereas innovation diffusion theory points to extending the boundaries of technical system performance modelling to societal systems.

To support innovation according to disruptive innovation theory, decision value analyses should be developed to integrally and objectively quantify and forecast the technology and value creating performance of the innovation for all stakeholders. This encompasses:

1) The joint modelling, quantification and forecasting of technical performance and economic, safety and societal metrics (see e.g., Faber, Qin et al. (2019)).
2) Decision value analyses with a base scenario, which should represent the conventional technology.
3) Decision theory is readily formulated to predict *ex-ante* outcomes of technology performance with a predicted information and predicted action decision analyses.

The perspective of innovation diffusion theory points to the societal boundaries of technical performance models. These boundaries have been worked on in the last decades with approaches and studies by, e.g., Murphy and Gardoni (2008), Faber, Miraglia et al. (2020), Ellingwood, Cutler et al. (2016). Although these works are in the context of sustainability, resilience and risk modelling, the basic concepts and their penetration into interdisciplinary technical and societal performance modelling may provide a ground to cover technology-society interactions.

First steps for decision support for integrity management technology readiness development have been demonstrated with value forecasting analyses to support technology screening, see Thöns, Irman et al. (2021), Costa, Thöns et al. (2023b) and Costa, Thöns et al. (2023a).

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