21ST INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

BREAKTHROUGH TECHNOLOGIES: PRINCIPLE FEASIBILITY DEBATES

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Abstract

Designing new technologies involves creating something that did not exist before. In particular, designing technologies with a low degree of maturity usually involves an assessment of its feasibility or infeasibility. Assessing the feasibility of a technology is of vital importance in many domains such as technology management and policy. Despite its importance, few publications actually deal with the fundamentals of technological feasibility such as feasibility proofs or proposing different feasibility categories. This paper addresses this gap by reviewing the existing literature on the feasibility of low-maturity technologies, proposes a framework for assessing feasibility issues, and reconstructs past and ongoing feasibility debates of four exemplary technologies. For the four technologies analysed, we conclude that sufficient expected performance is a key feasibility criteria to all cases, whereas physical effects and working principles were issues for more speculative technologies. For future work, we propose the further development of feasibility categories for different technologies of different degrees of maturity.

Keywords: Systems Engineering (SE), Technology, Conceptual design, Early design phases, Uncertainty

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 2: Design Processes | Design Organisation and Management, Vancouver, Canada, 21.-25.08.2017.

1 INTRODUCTION

A breakthrough technology in the following is defined as a technology that offers a radically new capability or a performance improvement of at least an order of magnitude. The innovation literature has considered these technologies in the context of “radical innovation”, although radical innovation encompasses a far larger set of technologies than breakthrough technologies, as it is not limited to capabilities and performance (Chandy and Prabhu, 2010; Garcia and Calantone, 2002; Kotsemir, 2013). The turbojet, inertial navigation, the Google search engine, and autonomous driving are breakthrough technologies. Breakthrough technologies are also considered to be fundamental for sustainable new business models (Masters and Thiel, 2014; Teller, 2013). These technologies can lead to radical changes to the status quo. The turbojet enabled fast and affordable intercontinental travel, inertial navigation enabled a whole class of systems such as long-range aircraft, rocket launchers, and ballistic missiles. The Google search engine enabled almost instant information retrieval from existing knowledge.

Fundamental questions about breakthrough technologies are how to assess their feasibility at an early stage, how to quickly reduce key uncertainties regarding feasibility, how to integrate the technology into a product, how to design the enabling systems required for its successful operation, and how to evaluate the readiness of the context into which the product is introduced. These are questions that have been addressed for technologies in general in the technology management literature (Burgelman et al., 1996; Schilling, 2013). Some exploratory proposals have been made regarding uncertainty reduction for breakthrough technologies (Drexler, 2009) and feasibility categories (Cleaver, 1977). The product development and systems engineering literature has previously treated the infusion of new technologies into an existing system architecture (Moullec et al., 2013; Suh et al., 2010). Furthermore, the systems engineering literature has proposed various metrics for assessing the maturity of a technology such as the Technology Readiness Levels (Mankins, 1995), Manufacturing Readiness Levels (Cundiff, 2003), and System Readiness Levels (Sauser et al., 2006).

However, breakthrough technologies have often characteristics that make their assessment challenging and most approaches from the literature no longer applicable. For realizing a radically new capability and/or an order of magnitude increase in performance, often, new physical effects and new working principles are used which require the assessment of principle feasibility. Furthermore, to create new business models, new operational principles have to be developed that allow for a proper exploitation of the capability or performance in the market place. There are also numerous cases where breakthrough technologies have been injected into products too early, which lead to a failure in the market place, as, e.g. enabling systems were not present. In successful cases, existing enabling technologies were quickly adapted in order to allow for a proper exploitation of the breakthrough technology, such as aircraft fuselages for the turbojet. For example, initial jet airplane designs were based on straight-wing designs, as they already existed, instead of swept wings that have a better aerodynamic performance but needed to be newly developed. The Google search engine would not have been successful without a large number of internet users and websites. The literature on the sociology of technology and technology history has dealt with this interaction and co-evolution of technologies (Bijker et al., 1987; Constant, 1980; MacKenzie, 1987).

Although other domains such as sociology and technology history have addressed breakthrough technologies, we argue that the existing product development and systems engineering literature has not yet addressed these technologies sufficiently to provide companies and policy-makers with guidance on how to assess these technologies.

As a first step towards addressing the initially mentioned research questions, in this paper, we deal with the question of principle feasibility. More specifically, with the questions what types of arguments were put forward for / against principle feasibility and how the feasibility issues were resolved. By “principle feasibility” we mean that a technology can possibly be realized regarding its underlying physical effects and working principles. This would correspond to the TRLs 0 to 3, where physical effects are confirmed and technology concepts formulated. Whereas TRL proposes a maturity metric, we are more interested in the debate around the feasibility assessment that enables a proper TRL classification. Principle feasibility seems to be debated before classic feasibility proofs such as prototypes or results from experiments exist. Although it might seem that principle feasibility regarding physical effects and working principles have a clear yes / no answer, we demonstrate by using records from historical and ongoing debates that converting physical effects into applicable engineering knowledge is not trivial and the framing of the feasibility question plays an important role.

In the following, we limit our focus on technologies as physical artifacts (hardware) along with their design (Hein, 2016; Olechowski et al., 2015). For software and algorithms, feasibility issues are more closely related to logic, proofs, and mathematics, e.g. calculability that seem to be quite different in nature from feasibility issues pertaining to physical artifacts.

We first conduct a literature survey on breakthrough technologies. Based on a conceptual model for physical technologies, we reconstruct four past and current feasibility debates to assess the types of arguments that are / were put forward. Finally, we assess, which elements of the conceptual model were subject of the debates, the associated types of arguments, and which technology elements then contributed to the resolution of the issue.

2 LITERATURE SURVEY

2.1 Definitions

In the following, we introduce a set of definitions. First of all, the term "technology" needs to be defined. According to Bijker et al. (1987), technologies fall into three categories:

- Physical objects or artifacts: bicycles, lamps, Bakelite;
- Activities or processes: steel making or molding (We would put algorithms, methods, instructions into this category);
- Knowledge pertaining to the first two categories: What people know as well as what they do.

In this paper, we rather focus on technology in the narrow sense of a physical object or artefact.

Next, the term "feasibility" needs to be defined. The definition for feasibility which is used in this paper is: "Capable of being accomplished or brought about; possible" (The Free Dictionary, 2016). "Feasible" can be substituted by "possible" or "can be realized" in the context of technologies and technical systems. Typical statements are:

- "Interstellar travel is feasible"
- "Artificial intelligence is feasible"
- "We have shown that a nuclear-electric mission to Jupiter is feasible."

As mentioned in the introduction, by "principle feasibility" we mean feasibility on the conceptual level of a technology, where the applicability or existence of physical effects and working principles for a technology are debated. Typical principle feasibility statements are:

- Is it feasible to use nuclear fusion for fusion reactors?
- Are artificial nanomachines feasible?

2.2 Feasibility Categories

Despite the importance of assessing principle technological feasibility, only few publications deal with the subject matter. Mankins (1995) introduces the Technology Readiness Levels (TRL) that are in widespread use today. Nevertheless, TRL is a metric for technology maturity and does not directly address feasibility. However, we can assume that a technology with a high TRL is feasible and vice versa. Cleaver (1977) presents four technology feasibility categories along with criteria for putting a technology into these categories. The categories were later adopted by Ruppe (1982). Kaku (2009) presents three impossibility categories. Although these publications have addressed principle feasibility, they do not seem to specifically address breakthrough technologies and their characteristics.

Next, we will present two methods for systematically increasing the feasibility of a technology.

2.3 Exploratory Methodologies

In the following, methodologies that are applicable to the development of breakthrough technologies are presented. In the context of general design theory, CK theory has been specifically presented as a design theory that captures conceptually what is not known (concept) and known (knowledge) in the process of designing (Hatchuel and Weil, 2009, 2003, 2002).

Regarding more specific methodologies that address breakthrough technologies, Eric Drexler coined the term exploratory engineering (Drexler, 1991), which can be defined as the "process of designing and analysing detailed hypothetical models of systems that are not feasible with current technologies or methods, but do seem to be clearly within the bounds of what science considers to be possible within the narrowly defined scope of operation of the hypothetical system model." (Wikipedia, 2016) Drexler contrasts exploratory engineering with what he calls "standard engineering" (Drexler, 1992, 2013, 2009). According to him, standard engineering leads to the manufacturing of a product. In exploratory engineering, design leads to understanding of what a future manufacturing process could produce.

The approach of exploratory engineering shares elements of "feasibility studies" that are common in areas dealing with long-term technology development such as in the space domain (Drexler, 2013). For example, the Concept Maturity Levels (CML) of NASA include an initial level that is called "initial feasibility" (Wessen et al., 2013).

The second method was proposed in Szabo (2007). Szabo argues that as long as experiments have not been conducted to verify or falsify the hypothesis that a technology works, it remains a "theoretical technology". He calls the study of theoretical technologies "exploratory engineering", referring to Drexler. He addresses the common problem of advanced technology that "exploratory engineers" claim that a technology is feasible, on the grounds of theoretical results, whereas scientists and engineers deem it infeasible, as it is not possible to implement it based on existing technology. He therefore proposes that designers "should design not only the technology but also a map of the uncertainties and edge cases in the design and a series of such experiments and tests that would progressively reduce these uncertainties. …We might call this requirement a requirement for a falsifiable design." (Szabo, 2007) Szabo acknowledges that the approach resembles the systems engineering approach in large novel technology programs. However, he associates the development of theoretical technologies with longer timescales and higher uncertainties. Sandberg and Bostrom (2008) use the approach for constructing a roadmap to whole-brain emulation, laying out steps towards this goal and major uncertainties.

Both Szabo and Drexler stress the differences between standard engineering practice and a practice that is suitable for assessing the feasibility of theoretical or speculative technologies.

3 A TECHNOLOGY CONCEPTUAL MODEL

For classifying feasibility arguments pertaining to breakthrough technologies, a proper conceptual model is needed that captures key elements of a breakthrough technology. As a starting point for such a model, the technology conceptual model from Hein (2016) is selected. The model was developed for physical technologies in the space domain and is adapted to a breakthrough technology context here. The resulting conceptual model is shown in Figure 1. We consider this conceptual model adequate in the context of this paper, as we limit our analysis to physical technologies.

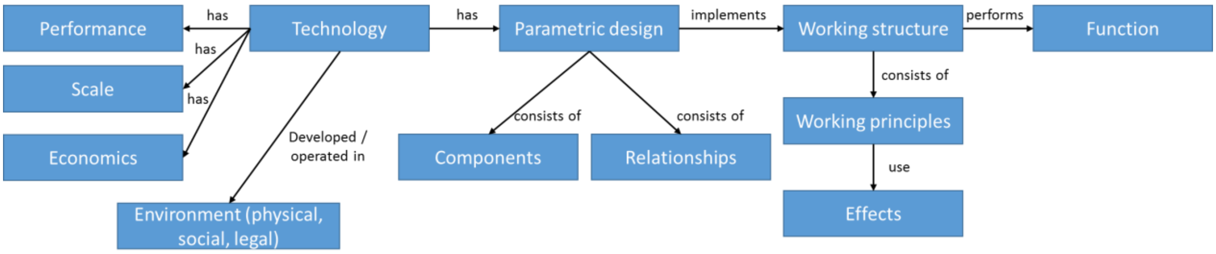

Figure 1. Technology conceptual model adapted from Hein (2016)

The basic elements of the conceptual model resemble previous work in product development, system architecture, and philosophy of technology (Arthur, 2009; Crawley et al., 2015; Otto and Wood, 2000; Pahl et al., 2007; Ponn and Lindemann, 2011; Vincenti, 1992, 1990). Such elements are the working structure, working principles, effects, and the function. Added elements are in particular the scale of the technology, performance, environment, and economics. "Scale" represents the size of the technology in the sense of its actual physical size or number of components integrated. Classic examples for technologies with different physical size scales are nuclear fusion reactors, rocket engines, and materials. The efficiency of fusion reactors increases with size. By contrast, rocket engines exhibit combustion instabilities at increasing size. Materials at the nano-scale behave differently than at the macro-scale (Drexler, 1992). Scale in the sense of integrated components are e.g. data centres or server farms where a large number of identical servers is integrated. Scale is important, as scaling up or down in some cases cannot be taken for granted due to potential nonlinearities, emergent behaviour, and changing physical effects.

We expect that performance is a key feasibility issue for breakthrough technologies. For example, the feasibility of inertial navigation was called into question on the grounds of quickly increasing errors in determining the vehicle's position. Hence, measurement accuracy as a performance indicator was a key feasibility issue.

The environment of a technology can be subdivided into its physical environment such as the larger system into which the technology is integrated, and its social and legal context. The social context represents the conventions and norms that may lead to accept, ignore, or reject a technology. This is different from the legal context, where non-compliance can lead to legal penalties.

Finally, economics in a broad sense consists of the underlying capital structure of the technology and its exchange value. Some technologies are very capital intensive to develop such as fusion reactors, clean tech, antibiotics. Others require less capital to develop such as most software programs. The exchange value of a technology is in most cases related to selling instances, collecting licensing fees, or transferring the complete of a technology along with personnel, documentation, etc.

Using this conceptual model, feasibility debates from the literature are analysed in the following.

4 PRINCIPLE FEASIBILITY DEBATES: FOUR CASE STUDIES

An exploratory analysis of four technologies with documented principle feasibility debates is conducted. In this section, we summarize the results of the analysis and discuss its implications.

We use the previously presented technology framework and literature on four historical and ongoing principle feasibility debates for (potential) breakthrough technologies. Based on the arguments retrieved from existing literature, argument maps are constructed for representing key arguments and relationships between these. The following four (potential) breakthrough technologies have been selected, due to their significance in the history of technology and due to the extent of available literature: turbojet (enabled airplanes to fly at unprecedented height and speed), inertial navigation (enabled navigation without external references), molecular assemblers (potential for precise manufacturing at a molecular level), EM drive (potential for space propulsion without exhaust mass).

We encountered two challenges when going through the literature dealing with these technologies. First, usually different positions exist on feasibility, notably feasibility arguments of advocates and feasibility arguments by critics (Morison, 1966). Second, arguments evolve over time, often with the state of knowledge. We address the first point by reconstructing the sequence of the arguments and counter-arguments of advocates and critics. We address the second point by either focusing on arguments around a tipping point in the perception of feasibility (inertial navigation, EM drive, turbojet) or a period where arguments seem to have remained rather stable (Molecular assembler). We acknowledge that for a more thorough temporal representation of the debate, the CK map could be more appropriate in representing the interaction between evolving concepts and knowledge (Hatchuel and Weil, 2009).

Table 1 shows the main element from the technology concept model for a technology on which the debate was focused and the main references we used for reconstructing the arguments. Some of the debates such as the Drexler-Smalley debate are well-documented. The debate took the form of a written exchange of positions. In other cases, such as Gamow's objection to inertial navigation, the original document is not accessible and has been reconstructed in MacKenzie (1993). For the purpose of this paper, it is sufficient to reconstruct the key arguments that were used. We also acknowledge that the documented arguments do not capture implicit biases, ignorance, relationship issues, and risk-aversion that may lead to perceiving feasibility in a favourable or opposite view as has been pointed out prominently by Morison (1966). It is clear that such factors are important to consider but are beyond the scope of this analysis.

Table 1. Technologies and main areas of feasibility debates

Technologies	**Main area of documented feasibility debate**	**Main references**
Jet engine	Performance limits of used materials	(Constant, 1980)
Inertial navigation	Performance limits of position measurement	(MacKenzie, 1993, 1987)
Molecular assemblers	Viability of precise atomic-level manipulations	(Bueno, 2004; Drexler, 2003a, 2003b; McCray, 2012; Smalley, 2003a, 2003b, 2001)
EM drive	Validity of physical effect via experiments, theoretical explanation and prediction of effect	(Millis et al., 2016)

We use an informal argument map to visualize the debates. The main feasibility claim is put at the top of the map, arguments that refute feasibility, mostly from critics, are linked to the claim by arrows with the label "opposes". Rebuttals of these opposing arguments, mostly by advocates, are linked to the opposing arguments by arrows labelled with "refutes".

The arguments for and against the feasibility of the turbojet are depicted in Figure 2. The main arguments put forward against its practical realization were the availability of materials with sufficient stress and temperature limits and a compressor with a sufficiently high compression ratio of ambient air (Constant, 1980, pp.184-186). These arguments were refuted by the availability of new high temperature alloys and the development of a new compressor with sufficiently high compression ratios by Griffith. Hence, the integration of new technologies into the turbojet lead to its principle feasibility.

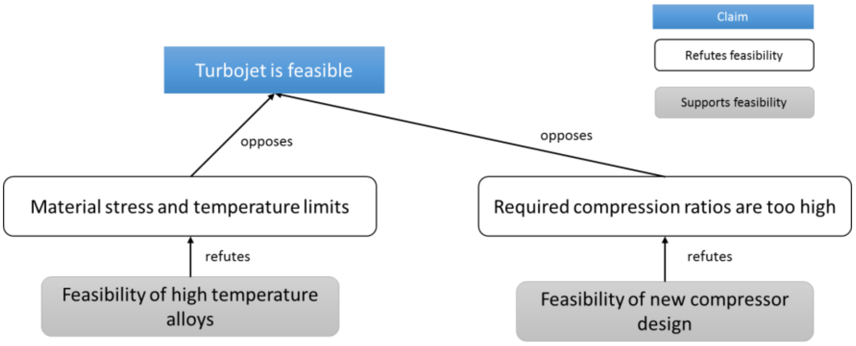

Figure 2. Argument map for and against the feasibility of the turbojet

The feasibility argument map for black-box inertial navigation is depicted in Figure 3. The main argument against inertial navigation was the so-called "problem of the vertical", put forward by eminent physicist Gamow. Gamow argued that according to the General Theory of Relativity, acceleration in a black box cannot be distinguished from gravitation. Therefore, black box inertial navigation is infeasible with sufficient accuracy, as the error would quickly increase. The argument was refuted by the development of a closed-loop control algorithm that calculates the position of the black box with respect to a spherical model of the Earth and readjusts the box, thereby minimizing the error to an extent where it could be used for practical applications.

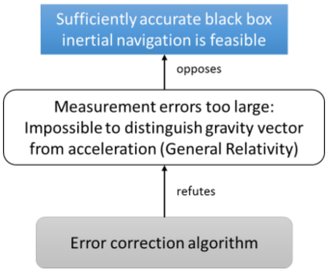

Figure 3. Black box inertial navigation feasibility argument map

The feasibility of hypothetical molecular assemblers has been debated in the Drexler-Smalley Debate (Bueno, 2004; Drexler, 2003a; McCray, 2012; Smalley, 2003a, 2003b, 2001). A reconstruction of the structure of the debate is shown in Figure 4

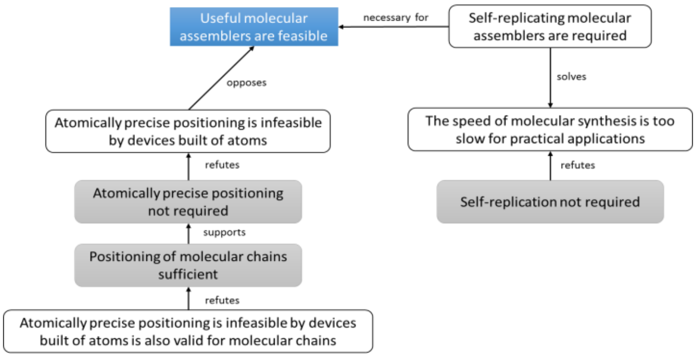

Figure 4. Molecular assembler feasibility argument map

Smalley rejects the feasibility of a molecular assembler that is capable of a) precisely positioning atoms and b) creating objects that are useful for practical applications. He rejects a), as he considers atomically precise positioning by devices made out of atoms impossible. He rejects b), as he considers manufacturing objects sufficiently quickly via molecular assemblers requires self-replicating assemblers, which are more challenging to develop than simple assemblers. Drexler argues against Smalley's points by pointing out that atomically precise positioning is not required, as instead of atoms, molecular chains are positioned, which relaxes the requirements for positioning. Smalley counters by claiming that his argument stays valid even for molecular chains. Drexler counters Smalley's self-replication argument by arguing that self-replication is not required and proposes possible solutions without self-replication.

As a final case, the current debate on the feasibility of the EM Drive is depicted in Figure 5, which is a yet to be confirmed propulsion system for spacecraft that seems to violate currently known physics. EM Drive proponents claim that they have measured a force when operating an EM Drive on a test stand (Shawyer, 2015; Tajmar and Fiedler, 2015; White et al., 2016). Some of the proponents further claim that the measured force is due to a thrust force generated by the EM Drive, which could indicate a yet unknown physical effect. Opponents are sceptical of these claims based on a) alternative explanations for the measured force, which would not imply that a thrust force has been measured; b) the used methodology and experimental setup to be able to measure a force with sufficient accuracy; c) the lack of theoretical models that predict the measured force (Millis et al., 2016).

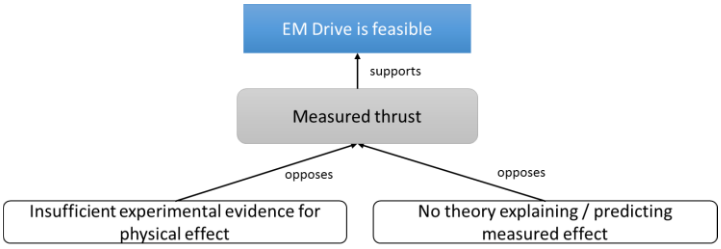

Figure 5. EM Drive feasibility argument map

The four argumentations for and against the feasibility of the respective technology are quite distinct but can be captured by the technology concept model presented in Figure 1. The resulting mapping is shown in Table 2.

Table 2. Feasibility debates and associated technology framework elements

Technology	**Elements of technology framework subject of the debate**	**Elements of technology framework that served as the solution**
Turbojet	Component performance (compressor, turbine)	New parametric design (compressor), materials (turbine blades)
Inertial navigation	Performance, working principle	Introduction of new working principle (new control algorithm)
Molecular assemblers	Physical effects, working principles, performance	New working principles (molecule manipulation)
EM Drive	Physical effect, working principle	Not resolved

In the following, the observations and implications of these results are reported.

As sufficient performance is a key criteria for breakthrough technologies, as expected, almost all debates focus on performance. Satisfactory performance was achieved for the turbojet via changes to the design, notably the parametric design (compressor), materials (turbine blades), and for inertial navigation by introducing a new working principle (new control algorithm). Hence, in both cases, new technologies on a component level were introduced to solve the feasibility issues. It seems that technology infusion into the architecture of a breakthrough technology is an important aspect. For the molecular assemblers, new working principles were introduced for achieving molecule positioning and sufficient manufacturing speed. The feasibility issues of the EM Drive have not yet been addressed.

Despite the small sample size, one can observe that the debates around more mature technologies (turbojet, inertial navigation) were focused on sufficient component and system-level performance, whereas debates around less mature technologies were focused on underlying physical effects and working principles. Nevertheless, performance was an important criteria in almost all cases. Another observation is that the feasibility issues were often resolved by injecting component technologies and working principles into the technology, without fundamentally changing the technology's architecture. If this observation can be confirmed by further case studies, it could be an important hint at how feasibility issues in breakthrough technologies can be systematically resolved.

We further observe that it is not necessarily the existence of a physical effect (e.g. Lorentz force) that is subject of the debate but its conversion into a working principle that satisfies the performance requirements of the application. Hence, principle feasibility debates are genuine engineering debates in the sense that it is not the knowledge of an effect that counts but its practical applicability, which is consistent with the distinct characteristics of technological knowledge, compared to scientific knowledge, as Vermaas et al. (2011) have pointed out.

Another observation is what we call "gap-filling". The many unknowns related to potential breakthrough technologies leads to the use of assumptions, analogies, and premises from existing technologies in order to fill the knowledge gaps. As Kurzweil (2003) remarked in the context of the Drexler-Smalley debate, arguments based on such premises can lead to straw man arguments that refute a technology concept that does not reflect the technology concept the advocates have in mind. Gap-filling seems to be highly sensitive to the domain, organizational, and cultural context in which the debate takes place along with the origin of its participants. Domain-sensitivity in the context of the Drexler-Smalley debate has been previously discussed in Bueno (2004).

5 CONCLUSIONS

Breakthrough technologies are technologies that introduce radically new capabilities or a performance increase of at least an order of magnitude. Examples are the turbojet, inertial navigation, and autonomous driving. However, a remarkable pattern for these technologies is that their feasibility seems to have been initially contested. Existing approaches for technology assessment such as the Technology Readiness Levels do not seem to be adequate for capturing the subtle dimension of assessing the potential of breakthrough technologies, as they rather focus on technological maturity. Important aspects such as performance, enabling systems, and contextual factors are not taken into account. This paper addresses the principle feasibility of breakthrough technologies by looking at what arguments for and against principle feasibility were/are used and how the feasibility question was resolved. For this purpose, we reconstruct past and ongoing principle feasibility debates of four exemplary breakthrough technologies using a technology conceptual model and argument maps. For the four technologies analysed, we conclude that sufficient expected performance was a key issue debated in all cases, whereas physical effects and working principles were issues for breakthrough technologies with a relatively low maturity. Principle feasibility issues for breakthrough technologies seem to be resolved by introducing new component technologies and working principles. For future work, we propose the use of case and field studies in order to explore contextual feasibility criteria for breakthrough technologies such as injection into existing system architectures, enabling systems, and market readiness.

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ACKNOWLEDGEMENTS

The authors would like to thank Claudia Eckert and Eric Drexler for their comments on an earlier version of this article.