A CONCEPTUAL FRAMEWORK FOR BREAKTHROUGH TECHNOLOGIES

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ABSTRACT

Breakthrough technologies introduce a radically new capability or a drastic performance improvement. However, the existing engineering design literature does not specifically pay attention to them. In this paper, we present a conceptual framework for breakthrough technologies, aiming for a more detailed characterization of breakthrough technologies. First, based on a literature survey, we reflect on the relationship between breakthrough technology and innovation. In addition, we explore the relationship between breakthrough technologies at the component and system level. Next, we propose a conceptual framework with dimensions in which breakthroughs may occur and the corresponding expansion of concepts and knowledge, drawing from C-K theory. We subsequently apply the framework to the case of a laser sail-propelled interstellar probe. We conclude that the relationship between component and system-level breakthrough technologies requires further exploration. Furthermore, the coupling between the breakthrough technology and market breakthrough in the form of a new business model seems interesting for future work.

Keywords: Technology, Systems Engineering (SE), Design theory, Breakthrough technology, Radical innovation

1 INTRODUCTION

"Breakthrough technology" literally means a technology that has broken through some kind of obstacle, barrier, or may indicate a sudden advance (Merriam-Webster Inc., 2004). It has previously been defined as a technology that introduces a "radically new capability or a performance improvement of at least an order of magnitude" (Hein, Jankovic, & Condat, 2017). Similar notions have been proposed in the technology management literature such as "game changer" (Rice, Colarelli O'Connor, Peters, & Morone, 1998), discontinuous innovation (Rice et al., 1998), breakthrough innovation (O'Connor & Rice, 2013), and technological breakthrough (Chandy & Tellis, 2000). Historical examples include the Wright Brothers airplane (controlled, sustained heavier-than-air flight) and the transistor (orders of magnitude smaller size and energy consumption than vacuum tubes). Each of these technologies has either introduced an unprecedented capability (Wright Brothers airplane) or an at least order of magnitude improvement in performance (transistor). Today, the Google search engine (machine-powered search) (Masters & Thiel, 2014) and self-driving cars (Teller, 2013) are prominent examples. Breakthrough technologies or their equivalents are considered key for sustained competitive advantage (O'Connor & Rice, 2013). Breakthrough technologies are at the origin of radical innovations, which transform or create a new market (Garcia & Calantone, 2002; Rice et al., 1998).

Despite their importance, the engineering design literature does not seem to have paid much attention to breakthrough technologies. One reason might be that the link between engineering design and innovation remains in general underexplored (Isaksson et al., 2019). The existing engineering design literature is primarily focused on how technologies, for example, in the form of working principles can be used in a new product (Pahl, Beitz, Feldhusen, & Grote, 2007). Furthermore, the literature deals with how technologies can be integrated into the architecture of an existing product (Smaling & de Weck, 2007; Suh, Furst, Mihalyov, & de Weck, 2010), the maturity of technologies (Fragola, Morse, Putney, & Diapice, 2010; Mankins, 1995; Sauser, Verma, Ramirez-Marquez, & Gove, 2006), and predicting the future performance of technologies in order to identify promising system architectures (Knoll, Golkar, & de Weck, 2018). No specific distinction between types of technologies is presented, except for its maturity (Technology Readiness Levels) and whether or not fundamentally different working principles are used (creative design vs. routine design). However, the technology management literature has recognized for a while that the type of technological innovation has important implications on which new product development process to choose (Rice et al., 1998;

Song & Montoya-Weiss, 1998). Rice et al. (1998) have argued that processes for incremental innovation are ill-adapted to radical innovation projects, making them more likely to be canceled. One of the reasons is the much higher uncertainty related to developing breakthrough technologies and finding a market (O'Connor & Rice, 2013; Song & Montoya-Weiss, 1998). Based on this literature, we argue that breakthrough technologies need to be treated differently in engineering design than other technologies.

In this paper, we propose a conceptual framework for breakthrough technologies, in order to provide a basis for future engineering design methods, specifically aimed at the development of products or systems using breakthrough technologies. Section 2 reviews literature from different domains, where breakthrough technologies and related concepts have been discussed, section 3 introduces the conceptual framework, and section 4 presents an application of the framework to a case study.

2 LITERATURE REVIEW

Having argued for the importance of treating breakthrough technologies in engineering design, we propose to shed more light on the relationship between innovation categories and breakthrough technologies. How are innovation categories assigned to breakthrough technologies? In a first step, we clarify what we mean by "technology" and then discuss the meaning of "breakthrough". For this purpose, we consult the technology management, technology history, and sociology of technology literature and finish with the innovation management literature.

2.1 Technology management, sociology, and history

Our definition of breakthrough technology can be firmly grounded in the technology management literature. According to Sahal (1981), a technology is defined by its main function and its performance characteristics. An example would be the function "generate thrust" for aircraft engines, where a crucial performance characteristic is the thrust-to-weight ratio. He calls this definition of a technology the *systems concept of technology*. Sahal (1981) argues that this definition is most appropriate for describing intrinsic technology-related dynamics, expressed by key performance parameters. As performance is by definition a key characteristic of a breakthrough technology, we will use the systems concept of technology in the following. From this point of view, a breakthrough exhibits a new main function (new capability) or performance discontinuities. The systems concept of technology also seems to be compatible with the way technologies are treated in the engineering design literature.

Performance discontinuities have been described in the technology history and sociology of technology literature. More specifically, in his study of the jet engine, Constant (1980) refers to the notion of "reverse salient". A reverse salient is caused by a component technology in a system that prevents the overall system to increase its performance. The propeller engine created a reverse salient for airplanes, preventing their evolution towards higher speeds and altitudes. A breakthrough occurs when a component technology removes the reverse salient. According to Hughes (1993), a reverse salient appears when a technological or socio-technological system is already on an evolutionary trajectory, on which its component technologies co-evolve (e.g. performance improvement of power plants and distribution network in an existing electrical network). However, we do not see an obstacle to using the notion of reverse salient for a system that is at the beginning of an evolutionary trajectory. Technological breakthroughs are associated with the beginning of an evolutionary trajectory (Chandy & Tellis, 2000). For example, the Wright Brothers needed to develop a sufficiently lightweight internal combustion engine for their airplane to take off. An insufficient performance of this component technology is one reason why crewed heavier-than-air aircraft did not emerge earlier (Chanute, 1899). At the beginning of an evolutionary trajectory, a *breakthrough* in one or more component technologies leads to *breakeven* performance at a system level, for example, to qualify as controlled, sustained, heavier-than-air flight. To give another example, Rose (1971) presents the case of fusion reactor development, where breakeven performance is linked to keeping the plasma stable over sufficient periods of time, in order to get more energy out of the reactor than has been put in.

An important conclusion from this stream of literature is that there is an important relationship between breakthroughs at the component technology and system level.

2.2 Innovation management

A breakthrough technology can be the basis of an innovation. In the following, we are particularly interested in the link between specific innovation categories and breakthrough technologies. Such categories are introduced in the innovation management literature, such as Chandy and Prabhu (2010), Garcia and Calantone (2002), Garcia (2010), and Kotsemir (2013). According to OECD (1991), innovation is "an iterative process initiated by the perception of a new market and/or new service opportunity for a technology-based invention which leads to development, production, and marketing tasks striving for the commercial success of the invention." This definition highlights two necessary ingredients of innovation: The invention linked to a technology and its commercial success.

These two elements of an invention appear consistently in existing innovation categorizations. Based on an extensive literature survey, Garcia and Calantone (2002) conclude that a common factor in existing innovation categorizations is that innovations are linked to different degrees of technological and/or marketing discontinuities. Incremental innovation implies minor discontinuities in one and/or the other. A radical innovation implies major discontinuities in both. It is an innovation that is based on a new technology and which drastically changes or creates a market. A really new innovation is between these two extremes and implies a major discontinuity in either technology or marketing. In light of this categorization, a breakthrough technology is a major discontinuity in technology. In case it leads to a minor discontinuity in marketing, it is a really new innovation. In case it leads to a major discontinuity in marketing, it is a radical innovation.

Furthermore, Rice et al. (1998) characterize major technological discontinuities more specifically. They call a technology a *game changer*, if it has the potential of a (1) 5-10 times performance improvement compared to existing products, (2) to create a basis for 30-50% reduction in costs; or (3) to have new-to-the-world performance features. Game changers seem to be very close to our notion of breakthrough technology, although the values for performance improvement differ (5-10 times versus 10 times). Chandy & Tellis (2000) distinguish between a technological and market breakthrough. A technological breakthrough is the emergence of a new technology at the beginning of the technology S-curve, whereas a market breakthrough is a discontinuity in the benefits generated by the technology.

Table 1 summarizes which innovation categories are compatible with a breakthrough technology. Radical innovations and really new innovations might be based on a breakthrough technology. Incremental innovations are in general not linked to a breakthrough technology.

Table 1: Comparison between breakthrough technology and major innovation categories from Garcia & Calantone (2002)

Attribute	**Breakthrough technology**	**Radical innovation**	**Really new innovation**	**Incremental innovation**
Major technology discontinuity	Always	Always	Sometimes	No
Major market discontinuity	Causes sometimes	Always	Sometimes	No
10 times performance improvement or new capability	Always	Sometimes	Sometimes	No

From the reflection of the notion of breakthrough technology with the existing technology management and innovation literature, we draw the following conclusions:

- A "breakthrough" can happen at the component technology and system level: If it happens at a component technology level, it could lead to a breakeven or even a drastic performance improvement of the overall system. However, we can also imagine a case where component technologies that are individually not breakthrough technologies are combined to a system and the system exhibits the characteristics of a breakthrough technology.
- Breakthrough technologies can be the basis for certain types of innovation: A breakthrough technology can be the basis for radical and really new innovations. A radical innovation combines a major technological discontinuity with a new market discontinuity. In a really new

innovation, the breakthrough technology introduces a major technological discontinuity, while the market discontinuity remains minor (Garcia & Calantone, 2002).

In order to develop engineering design methods specifically for breakthrough technologies, we need to further deepen our conceptual understanding of breakthrough technologies. For this purpose, we will present a conceptual framework for breakthrough technologies in the following section.

3 A CONCEPTUAL FRAMEWORK FOR BREAKTHROUGH TECHNOLOGIES

In the following, we present a conceptual framework for breakthrough technologies. We combine Concept-Knowledge (C-K) theory (Hatchuel & Weil, 2003) and breakthrough dimensions based on Abernathy & Utterback (1978). Both integrate concepts from a variety of domains such as design science, innovation management, sociology of technology, technology management, and technology history. We select these two generic frameworks, as our aim is to integrate concepts from different streams in the literature.

C-K theory is a widely cited theory of design. It distinguishes between *concept* and *knowledge*. A *concept* is an object for which the logical status of some of its propositions, for example, its existence, is unknown (neither true nor false). An example is an antibiotic without resistance. We do not know if such an antibiotic exists. Another example is a flying taxi. It is an object whose status is yet unknown in terms of its function, performance, etc. *Knowledge* encompasses propositions with a known truth value (either true or false). For example, we know that antibiotics exist or airplanes can cross the Atlantic. We use "concept" and "knowledge" in a rather informal way in the rest of the paper, where "concept" stands for a new conceptual idea and "knowledge" for different forms of knowledge or know how. We are primarily interested in categorizing novelties in terms of concepts and knowledge. We distinguish between four categories of novelty, shown in Table 2. These different levels of expansion in C or K allow for a more detailed distinction between cases where something *new* is created conceptually (a new design, a new function, etc.) or new knowledge is developed (gaining experience with a design, function, etc.).

Table 2: Novelty categories in terms of C-K expansion

ΔC-δK: Conceptual innovation - New conceptual idea but minor knowledge expansion (Example: chair without legs) (Hatchuel & Weil, 2003)	**ΔC-ΔK:** New concept and major knowledge expansion (Example: cloud chamber)
δC-δK: Minor concept and knowledge expansion	**δC-ΔK:** Applied science - Existing concept but major knowledge expansion (Example: quartz watch) (Hatchuel & Weil, 2003)

We further derive a set of breakthrough dimensions from the literature. Dimensions from Abernathy & Utterback (1978) are a technology's performance, usage in terms of operations, value for stakeholders in terms of "identification of an emerging need or a new way to meet an existing need", and the business model. These dimensions correspond to different dimensions of breakthroughs (technology and market breakthroughs). Some of these dimensions also exist in the engineering design literature such as usage (Pahl et al., 2007) and value (Crawley, Cameron, & Selva, 2015). The business model links to the business literature (Demil & Lecocq, 2010; McGrath, 2010; Osterwalder, 2004; Teece, 2010). Additionally, we add the dimension of engineering and physical principles, in order to account for the major technological discontinuity of a breakthrough technology (Henderson & Clark, 1990). This dimension also helps to distinguish a breakthrough technology from incremental improvements that can also lead to large increases in performance when accumulated (Abernathy & Utterback, 1978).

We propose a matrix representation for the breakthrough technology framework. We construct this matrix by putting C and K expansions into columns and breakthrough dimensions into rows, as shown in Table 3. The first two rows are characteristics of a breakthrough technology and the last three characteristics of a market breakthrough. Combined, they are characteristics of a radical innovation. An entry under δC-δK indicates that only a minor discontinuity has occurred and the row criterion is not satisfied. ΔC-δK or δC-ΔK indicates that a major discontinuity has occurred but whether or not it satisfies the row criterion has to be decided on a case to case basis. Finally, ΔC-ΔK is a major discontinuity and satisfies the row criterion.

Table 3: Matrix with breakthrough dimensions as rows and degrees of C-K expansion as columns for the Wright Flyer in 1903

<table>
<tr><th></th><th></th><th></th><th>ΔC-δK</th><th>δC-ΔK</th><th>ΔC-ΔK</th><th>δC-δK</th></tr>
<tr><td rowspan="5">Radical innovation</td><td rowspan="2">Breakthrough technology</td><td>New engineering / physical principles</td><td></td><td>Known airplane engineering principles were significantly expanded in terms of knowledge (aerodynamic coefficient, control, engine performance)</td><td></td><td></td></tr>
<tr><td>New function / improved performance</td><td></td><td></td><td>Novel function (controlled, crewed, heavier-than-air flight) and performance (staying in the air for about a minute)</td><td></td></tr>
<tr><td></td><td>New usage</td><td colspan="4" rowspan="3">Not yet defined</td></tr>
<tr><td></td><td>Value for stakeholders</td></tr>
<tr><td></td><td>New business model</td></tr>
</table>

We use the Wright Flyer example in 1903 when the first controlled flights were executed. The Wright Brothers rigorously expanded knowledge about airplane design and combined component technologies to create a functioning airplane. Although some of the component technologies were inventions such as wing-warping for control, the bi-plane aircraft, airfoil, and internal combustion aircraft engines (Manly–Balzer engine in 1901) all existed prior to the Wright Flyer. Hence, in 1903 the Wright Flyer was a breakthrough technology, introducing the new capability of controlled, crewed, heavier-than-air flight. Nevertheless, no clear application of the technology existed at that point, which leaves the last three rows empty. Hence, we argue that the Wright Flyer in 1903 was a breakthrough technology, primarily due to the new capability it introduces but is not yet a radical innovation.

We also demonstrate that the matrix can be used for characterizing a (potential) breakthrough technology at different points in time. In 1909, the Wright Flyer was proposed as a military observation airplane. The result is shown in Table 4. A striking observation is that the application of the Wright Flyer as a military observation airplane was conceptually new, with little prior knowledge at the point of introduction. This led to a major knowledge expansions of how to use an airplane for this purpose. Only minor changes in new engineering and physical principles are observed, mainly focusing on incremental improvements in reliability. A major expansion of C and K occurs in terms of using an airplane for military observation. The Wright 1909 Military Flyer is the first airplane to satisfy the performance requirements for a military observation airplane. It thereby creates a new market for military observation airplanes with a new business model of selling them.

Table 4: Breakthrough dimension – novelty matrix for the Wright 1909 Military Flyer

	ΔC-δK	δC-ΔK	ΔC-ΔK	δC-δK
New engineering / physical principles				Increase in reliability of initial Wright Flyer and minor design changes
New function / improved performance			Novel function and performance for the military context without sufficient prior knowledge of military needs	
New usage			Operations of military observation airplane	
Value for stakeholders			Observation aircraft for the military	
New business model			Selling military airplanes with superior mobility over balloons	

A remaining task is to define the notion of *potential* breakthrough technology, which hinges on the interpretation of “potential”. For example, the first internal combustion engine was developed by Huygens in the 17th century but the engine fell apart after a few cycles (Huygens, 1680). Huygens somehow had the propulsion of vehicles in mind as an objective. However, neither a vehicle was developed nor was one conceptualized (Huygens, 1680). Hence, we feel that it does not qualify as a potential breakthrough technology for the reason that it was not intended to create a breakthrough. Hence, we can formulate minimal conditions for a technology qualifying as a potential breakthrough technology:

- A *clear formulation* of where the technology might cause a potential breakthrough (for which higher-level system, market etc.), similar to the articulation that a technology will be a “game changer” (Rice et al., 1998));
- *A reasonable extrapolation* of performance values from the prototype indicates that the breakthrough is likely to occur.

Another challenge is the distinction between different hierarchical levels (system or component level). This distinction is often neglected in the technology management and innovation literature but is important in engineering design. Is the jet airplane (system) the breakthrough technology or is it the jet engine (component technology)? We argue that breakthrough technologies can indeed emerge at different hierarchical levels. For example, the jet engine led to immediate improvements in thrust to weight ratios of about an order of magnitude. This improvement led to the elimination of the reverse salient that existed in airplanes in terms of flight altitude and velocity. On the other hand, jet airplanes themselves lead to drastic performance improvements that opened up new areas of activity (stratospheric flight) that would count as breakthroughs. However, as the case study in Section 4 shows, a combination of non-breakthrough component technologies can lead to a breakthrough on the system level and vice versa.

To summarize, a breakthrough technology is qualified by a breakthrough on one or more technological attributes such as an order of magnitude performance increase, a radically new capability, or/and new engineering and physical principles. Additional breakthroughs can be associated with a breakthrough technology, for example, the removal of a reverse salient in an existing system or reaching breakeven performance for a new system. If the technology also creates a new usage, value proposition, market, or business model, it would qualify as a radical innovation.

4 CASE STUDY: BREAKTHROUGH STARSHOT

We apply the previously developed framework to a gram-sized spacecraft for a mission to another star, which is currently under development by the Breakthrough Starshot program (Lubin, 2016). We will first apply the breakthrough dimension – novelty matrix to this technology and subsequently, briefly address the question of whether or not this is a potential breakthrough technology.

The data for this case study was collected from a conceptual feasibility study of the Initiative for Interstellar Studies (i4is) prior to the announcement of the Breakthrough Starshot program in March 2016. The lead author of this article participated in this study as the system architect. A team of 14 people has collaborated virtually for a week to analyze various concepts for sending a spacecraft with a mass of 23 grams to the Alpha Centauri star system. The results of the feasibility study (Hein, Long, et al., 2017) were subsequently reviewed by members of the Breakthrough Starshot committee and informed the Breakthrough Starshot program. As data sources, published reports, internal documents, and personal accounts from team members were used.

The concept for the Breakthrough Starshot mission was proposed in Lubin (2016). The spacecraft consists of a power subsystem (small-scale nuclear battery), communication subsystem (laser optical communication), camera payload, and further typical spacecraft subsystems. In addition, a thin, highly reflective surface is attached to the spacecraft, which is intended to reflect an incoming laser beam. This sail-like structure is called laser sail. By reflecting the laser beam, thrust is generated. The laser beam is emitted by a ground-based laser beaming infrastructure with a beam power of about a hundred gigawatts. The spacecraft is put into an orbit around Earth and then accelerated via the laser beam to velocities of 10-20% of the speed of light, reaching the Alpha Centauri star system within 50 years, in order to send back photos of potential exoplanets. Figure 2 shows a swarm of these spacecraft approaching the Alpha Centauri star system.

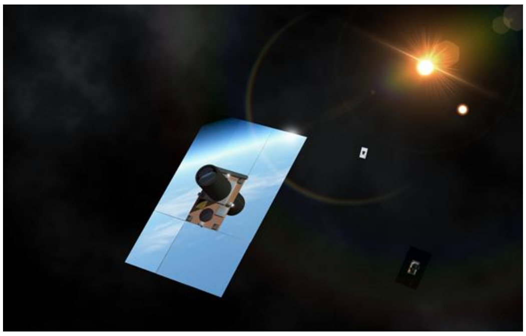

Figure 2. Concept for a gram-sized interstellar probe (Hein, Long, et al., 2017)

For applying the breakthrough technology framework, we first need to define the system and component technologies. We treat the combined spacecraft and beaming infrastructure as the system. The key component technologies are the fiber-optic lasers that form the phased laser array and the laser sail which consists of a highly reflective dielectric material. A phased laser array prototype for the beaming infrastructure has been tested in a laboratory environment (Lubin, 2016). However, scaling these lasers up to hundred gigawatts of beaming power requires additional technologies such as the development of new types of beam guides for assuring the coherence of the beam. In addition, such high power densities have not yet been applied to reflective surfaces such as the laser sail. New, unknown physical effects could occur. Laser sail materials with the required reflectivity (99.999%) do exist. However, it is unlikely that the same substrate material (glass) can be used.

Is this system a potential breakthrough technology? It is clear that the underlying engineering and physical principles are new. But we also need to look at the potential performance, which is the velocity of the spacecraft. Reaching a nearby star within 50 years requires a thousand-fold increase in velocity compared to the fastest spacecraft that have left our Solar System. Both technological breakthrough criteria are satisfied on the system level as well as both potential breakthrough technology criteria. Hence, we are dealing with a potential breakthrough technology. Table 5 shows the resulting breakthrough dimension - novelty matrix for the Breakthrough Starshot system.

Table 5: Breakthrough dimension – novelty matrix for Breakthrough Starshot system

	ΔC-δK	**δC-ΔK**	**ΔC-ΔK**	**δC-δK**
New engineering / physical principles			First fast laser sail propulsion system with still many unknowns related to underlying engineering principles	
New function / improved performance			Potentially orders of magnitude higher probe velocities; large functional knowledge expansion	
New usage			Operation of the beaming system and spacecraft swarm novel and knowledge to be developed	
Value for stakeholders			Potentially interstellar exploration based on large spacecraft numbers: Value yet to be explored	
New business model	Not yet defined			

Is this breakthrough enabled at the system or component level? Component technologies are combined, in order to deliver a new capability at the system level (reaching another star within a human lifespan). These component technologies exist at least as prototypes. Low-cost, high efficiency lasers are now available, due to an exponential decrease in cost and continuous increase in efficiency over the last decades, miniaturization is moving spacecraft from tons to kg-sized spacecraft to gram-sized spacecraft, and novel, highly reflective, light-weight laser sail materials are under development (Atwater et al., 2018). Nevertheless, it seems that these technologies are rather a result of an accumulation of incremental improvements.

Table 6 shows the breakthrough dimension – novelty matrix for the laser sail component technology. Some of the potential materials for the laser sail are based on new engineering and physical principles, such as meta-materials and nano-engineered materials (Atwater et al., 2018). These materials imply a considerable conceptual and knowledge expansion. Regarding performance, the conceptual expansion is rather minimal, as using laser sails for propulsion is a well-known concept. However, the knowledge of doing so at extremely high power densities requires a significant expansion of existing knowledge in how to engineer the sail at the nano, micro, and macro-scale.

Regarding usage, the proper operation of a laser sail under space conditions is still subject to numerous unknowns, starting from deployment and its behavior during the propulsion phase. The potential value for stakeholders is relatively clear (sail for in-space propulsion). However, the knowledge of how to exploit the sail for this purpose is still to be developed. A new business model has not been defined. To summarize, the laser sail seems to be rather based on an expansion of knowledge, rather than the introduction of a new concept. Only for some of the potential materials under consideration, it would qualify as a potential breakthrough technology.

Table 6: Breakthrough dimension – novelty matrix for Breakthrough Starshot: Laser sail

	ΔC-δK	**δC-ΔK**	**ΔC-ΔK**	**δC-δK**
New engineering / physical principles			New material concepts with different engineering and physical principles	
New function / improved performance		Existing sail function but different functional knowledge		
New usage		Known usage in interstellar mission but significantly different operational parameters		
Value for stakeholders		Known value for system developers but different knowledge required for exploiting value generated		
New business model	Not yet defined			

To conclude, combining component technologies that are not necessarily breakthrough technologies themselves, may lead to the creation of a potential breakthrough technology.

An observation from this exercise is that it is important to carefully define the reference point for the analysis. Is Breakthrough Starshot compared to existing propulsion systems or is it compared to the prior art of laser sail propulsion concepts? Is the knowledge expansion assessed with respect to a specific organization or in general (Garcia & Calantone, 2002)?

Finally, the study focused on technological feasibility, using calculations based on physics principles for fundamental mission parameters and on financial feasibility, using high-level analogy cost calculations. The approach partly resembles the Exploratory Engineering approach proposed by Drexler (2013) but was supplemented by the engineering knowledge categories presented in Vincenti (1992), including typical engineering considerations such as using extrapolations from existing spacecraft components.

5 CONCLUSIONS

In this paper, we propose a conceptual framework for breakthrough technologies, in order to provide a basis for future engineering design methods, aimed at the development of products or systems using potential breakthrough technologies. A breakthrough technology is a technology that achieves a breakthrough, e.g. removing a reverse salient, achieving a 10 times performance increase, or introducing a radically new capability. We apply the framework to the case study of a laser-sail propelled interstellar probe, which is currently under development. The case study demonstrates, how the conceptual framework captures various subtleties that emerge during the assessment of a potential breakthrough technology. We conclude that the relationship between component and system-level breakthrough technologies requires further exploration. Furthermore, the coupling between the breakthrough technology and market breakthrough in the form of a new business model seems interesting for future work.

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