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Supporting Decision Making in Technology Standards Battles Based on a Fuzzy Analytic Hierarchy Process

Geerten van de Kaa, Eric van Heck, Henk J. de Vries, Jan van den Ende, and Jafar Rezaei

***Abstract*—In many markets, battles are fought over technology standards. Often, these battles result in a single standard that achieves dominance. Decision making in standards battles is complex due to the lack of insights about the factors that influence the outcome of such battles. These include the characteristics of the standard, the stakeholders, the standard supporters, and the standard support strategies. The importance of these factors determines the dominance of a technology standard. This study investigates the usability of a multiattribute utility approach named fuzzy analytic hierarchy process in decision making in technology standards battles. Three technology standards battles are analyzed using a fuzzy analytic hierarchy process approach. The empirical results show that the outcome of these standards battles is not fully characterized by path dependency, but that factors for standard dominance can be used to explain the outcome of these battles. We show that it is possible to model the process of standard selection. The fuzzy analytic hierarchy process decision support tool is useful to determine the relative weight of factors for standard dominance, and can be successfully used in decision-making problems relating to standardization.**

***Index Terms*—Analytical hierarchy/network process, decision support systems, decisions under risk and uncertainty, fuzzy and gray systems, management of innovation, strategic management of ITT, technology diffusion.**

I. INTRODUCTION

IN many markets, battles are fought over technology standards. Often, these battles result in a single standard that achieves dominance mainly through network externalities [1], [2]. These externalities are common in markets where technologies need to be connected together into one network (e.g., a network of home appliances) and in two-sided markets [3], [4] where standards coexist with complementary goods. Once a standard has achieved dominance, a whole range of stakeholders (including manufacturers, distributors, and consumers) can benefit from the increased compatibility that the standard enables, and customers can benefit from lower priced complementary goods in which the standard is implemented. Shapiro and Varian [5] refer to these markets as "winner takes all" markets. Firms that sponsor the winning standard will earn most if not all of the rewards whereas the firms that sponsor the losing standard sometimes have to leave the market. Once a standard has been adopted, a wide assortment of complementary goods and services may be developed, possibly resulting in an industry ecosystem that extends far beyond the single technological standard [6]. Consequently, winners may become platform leaders [7] and may appropriate even more of the rents provided by the standard.

Economics and management researchers have started to analyze how firms compete in these network markets [8], [9]. These scholars use the term "standards battles" or "platform wars" to refer to a situation in which different incompatible standards contest for market dominance [5], [10]. Examples of standards battles include VHS versus Betamax [11] and, more recently, Blu-ray versus HD-DVD [10]. For the parties involved, it is important to have insights into the chances of a specific standard becoming dominant. Firms want to know which standard to support and implement. Consumers will prefer to spend their money on products that incorporate a winning standard; otherwise they may face problems related to interoperability with other products and/or may lack future support for their products. We have identified a comprehensive set of factors that can explain the outcome of these standards battles. Researchers as well as practitioners face the problem of how to combine all these factors in order to better understand a battle and to assess which technology is in the best position to win the battle. Companies then can bet on the winning horse or may be in the position to influence the outcome of the battle in their favor.

In this paper, we provide a solution to this problem by developing a framework for standard dominance that is embedded in a decision support system. The overall objective is to explore whether such a system is useful in supporting decision-making in complex technology standards battles. This paper adds to the growing body of the literature focusing on dominant designs and standardization [12]–[14].

Different categories of standards exist [15]–[17]. We address situations in which technologies need to be physically connected together into one network. Therefore, we focus on compatibility standards; standards that give requirements for interrelated entities to enable them to function together. This category of

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standards has the clearest market impact, and is also the category to which the literature on standards battles usually refers. We focus on the battle between compatibility standards that are sponsored by one or more actors. Therefore, we focus on *sponsored* compatibility standards; codified specifications defining the interrelations between entities so that they can function together [18], [19], and in which one or more actors hold a direct or indirect proprietary interest [15], such as Sun's JAVA [20].

A standard is considered to be dominant when it has achieved more than 50% market share among new buyers in a certain product or service category and holds that share for a significant amount of time [12], [21]. Basically, the dominance of a standard depends on its selection by its potential users. These users include firms that develop products in which the standards are implemented and customers who buy those products. If a majority of these users choose one particular standard, then that standard will achieve dominance. The user of a standard can essentially be seen as a decision maker. Thus, the selection of standards can be seen as a decision-making problem and can be analyzed as such [22]. For firms, deciding which standard should be supported is a strategic one, which requires meeting many (often conflicting) criteria [23]. A multiattribute utility approach might be suitable in this case. If there are many criteria and it is difficult for decision makers to compare them, a method in which judgments can be made easily is preferred. We analyzed decision-making theories and found a suitable approach in the analytic hierarchy process (AHP) [24]. We use this approach to compute weights for the factors that determine the outcome of standards battles. By doing so, we examine the usability of the AHP in standardization.

II. Literature Review

In the literature, there is a debate on whether the outcome of standards battles is a result of path-dependent processes, which are random and beyond the firm's control, or whether the firm can manage these events. Some scholars have emphasized the path-dependent nature of standards battles [25], [26]. "Historical small events" (that are not necessarily known in advance) may decide the outcome of standards battles [15]. A random idiosyncratic event may occur and as a result some people may choose to adopt a certain standard. This may lead to a bandwagon effect [2] resulting in other people adopting the standard until eventually that standard achieves dominance. Standards-based industries are characterized by increasing returns to adoption and often exhibit demand side economies of scale. This means that the rate of return from a technology increases with the number of users that adopt that technology. This severely increases the significance of path dependencies. A classic example of the path dependency phenomenon is the story of the QWERTY keyboard layout standard [26]. At the end of the 19th century, the first typewriter was introduced. The choice was made to position the letters of the word "typewriter" in the upper row so that salesmen could easily demonstrate how fast they could type [26]. As more people adopted the machine, a bandwagon effect occurred and people were soon locked into the keyboard layout standard. With the transition from typewriters to keyboards, people did not switch to more efficient keyboard layout standards such as DVORAK since switching costs were too high. Consequently, now, the consumer is locked in the QWERTY keyboard layout standard. This case illustrates the path dependency concept in standards battles; choices made in the past influence the set of possible choices in the future. If we strictly follow this theory, it would be difficult, if not impossible, to predict the outcome of a standards battle since unexpected events can always happen and these may tip the balance toward a certain standard [15]. Then, the process of technology selection would be unsuitable for modeling. However, as pointed out by other scholars [12], [14], these unexplainable events may, in fact, be antecedents to known factors for standard dominance. Firms may attempt to influence these known factors to increase the chances that a certain standard achieves dominance.

Technology management scholars have proposed several factors that may influence the outcome of standards battles [5], [12], [13], [21]. However, their frameworks tend to be incomplete and overlapping. Suarez [12] distinguishes between firm-level factors and environmental factors, both of which directly influence standard dominance. Lee *et al.* [21] refer to these latter type of factors as "external conditions" which characterize the market in which the battle is fought. These environmental factors affect the magnitude of the effect of firm-level factors on standard dominance. For example, in an industry characterized by network externalities, an actor developing a technology for which complementary goods do not exist will have a lower chance of achieving dominance with that technology [13]. Further, these factors affect the speed and likelihood of standard dominance. Standardization literature has examined how individual organizations and consumers adopt standards [27], and has studied the role of standardization organizations, and the willingness to adopt a certain standard [19]. Leiponen [28] analyzes the effect of a firm's position in a network on its formal standard setting influence. The topic has also been studied from a game theory perspective [29], [30]. However, these studies and also some quantitative empirical studies [14], [31] only focus on a subset of the total number of possible factors. Finally, some case study-based research [11], [18], [32] addresses multiple factors, but does not consider the actual weights of each factor. Although every battle for standard dominance is fought in a different arena and therefore it is difficult to assign weights to each factor, we believe that patterns of weights might apply in certain cases. Discovering such patterns would make it easier to explain and predict the dominance of standards within those particular cases.

Management science scholars have played a significant role in the development of decision-making theories [33]. Basically, we can distinguish three perspectives in decision making: normative, descriptive, and prescriptive [33]. The normative perspective focuses on how to make the best decision assuming a decision maker is fully informed and makes rational choices. The axiomatic foundations of decision theory (i.e., the assumptions that people make when reaching decisions) were formed from this perspective. In the 1980s, the emphasis shifted from solving the actual decision problem to the decision makers and their behavior [34]. The descriptive perspective focuses on behavioral

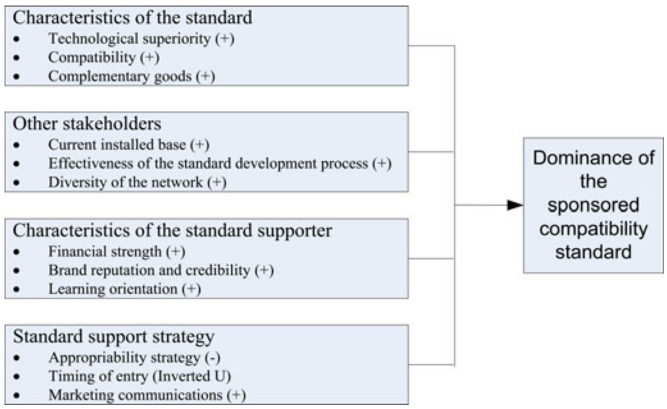

Fig. 1. Research model.[1]

decision making and on how people diverge from normative approaches, and examines whether judgments correspond with actual decisions. In prospect theory, for example, judgments from people are seen as positive or negative deviations from a certain point of reference [35]. The prescriptive perspective focuses on helping people make better decisions, and makes use of both normative and descriptive perspectives. Drawing from optimization theory, another school of thought within management science, multiple criteria decision making (MCDM) was developed in the early 1970s as a prescriptive theory for decision making [23]. Here, the goal is to aid decision makers in finding the best possible solution to a decision problem, consistent with their preferences [34]. In MCDM, the value function is explicit, meaning that the decision-maker's preference for alternatives is rated by directly taking into account the existence of a value function, but not by actually assigning weights to criteria present in the value function. For instance, the decision maker is presented with all possible solutions and, on that basis, chooses an optimal solution [34]. Multiattribute utility theory (MAUT) is often seen as a part of MCDM and deals with situations where preferences for the value function are articulated interactively with (or prior to) the rank order of the alternatives [34]. The value function is thus implicit. In MAUT, an additive value function is defined in which it is supposed that one alternative is preferred over another if its utility is larger [36]. If uncertainty and risk play an important role in the assessment of alternatives, MAUT is treated separately from MCDM [34], [37], [38]. A high level of uncertainty is present when the decision is taken, since it is unknown which standard will reach dominance. Sometimes the uncertainty is too high and decisions are postponed. In this study, we have chosen to apply a multiattribute utility approach to standard selection. By doing so, we explore whether this approach can be used to decrease uncertainty and support decision making.

III. Framework for Standard Dominance

Fig. 1 presents a framework for the selection of standards based on the literature review. We identify four categories of factors for standard dominance that can be directly influenced by the firm. These are characteristics of the standard, other stakeholders, characteristics of the standard supporter, and standard support strategy. The factors are listed together with their directions as reported in the literature.

On the basis of prior studies [5], [9], [12] and other conceptual and empirical literature on factors for standard dominance, we use the set of factors that has received the most attention in the literature. In a separate file (which is available upon request), we provide a list of studies used to compile this list of factors. Surprisingly, none of these studies assigns weights to factors for standard dominance. Next, we examine these factors.

A standard that has superior characteristics compared to other standards may have a higher chance of achieving dominance. This superiority may include technological superiority, compatibility, and availability of complementary goods. Schumpeter [39] defines *technological superiority* of a standard as having superior features that make this standard outperform other standards. For example, if the data rate or bandwidth capacity of standard A is higher compared to standard B, then standard A is superior in terms of technology. However, the most technically advanced or the best standard does not necessarily become the dominant one [26]. For example, as discussed earlier, the QWERTY keyboard layout standard was technically inferior to DVORAK but due to path-dependent processes, the former standard maintained dominance. Another characteristic of a standard that can add to its superiority is the *compatibility* that the standard enables. Standards can be designed in such a way that they are backward compatible with the previous generation of the standard so that products that implement an old generation of the standard can still be used together with products that implement the new generation of the standard. This increases the chances of the standard achieving dominance [40] as it can utilize the standard's previous installed base. Teece [41] defines *complementary goods* as those "other" goods needed to successfully commercialize a certain standard. If complementary goods are needed for a standard to function optimally (which is often the case) and these goods are available in high quantities, the value of a technology will increase as more diverse complementary goods are available. This plays a key role in the video gaming industry; the value of a gaming console to a user is heavily dependent on the availability of complementary goods (games) [32].

The second group of factors relate to stakeholders other than the main standard supporter that affect the outcome of the standards battle. Many authors mention installed base as a factor. The *current installed base* of a standard is the number of users of that particular standard. If network externalities exist in a market, the value of a technology depends on the installed base of users [1]. This means that a standard increases in value the more it is adopted by other users. For instance, if a mobile telephone only has one user, the mobile phone accrues no value from network externalities. However, if more users adopt the mobile phone, more users can be reached through that phone and thus the value of the phone increases. A self-reinforcing pattern can arise through network externalities, resulting in an initial advantage for a standard to achieve dominance. Standards

[1] This model is the result of prior research [98].

may be developed in various organizational settings including alliances, consortia, and committees. The *effectiveness of the standard development process* within these settings affects the likelihood of the standard to become dominant in the standards selection stage [42]. For example, certain decision rules can cause a lengthy delay in the decision-making process [19], potentially leading to an obsolete standard once adopted [43]. Several characteristics of the network of stakeholders supporting a standard can have a positive influence on the chances that a standard will achieve dominance. The emphasis in this study lies on the *diversity of the network* [44]. This refers to the extent to which relevant stakeholders are represented in the group of standard supporters. A standard that is supported by a diverse network in which stakeholders represent each relevant product market for which the standard serves a defining role will have a higher chance of achieving dominance [44], [45]. For instance, in the digital video disc standards battle, hardware manufacturers worked together with movie studios to establish the DVD standard [46], [47]. In the home video game console industry, a diverse network with firms that develop games of different genres will attract more different users. This contributes to standard dominance [31].

The third group of factors relates to the strength of the standard supporter. The stronger the standard supporter, the higher the chance the supported standard becomes dominant. *Financial strength* of the standard supporter is related to the current financial condition of the standard supporter and its future prospects, and positively affects standard dominance [48]. Firms which have more financial resources may spend more money on marketing campaigns [49] or can give away more complementary goods for free. The *brand reputation and credibility* refers to the opinion people have about a group of standard supporters, based on what has happened in the past. This plays a significant role in users' selection of a standard, since past performance in setting dominant standards has a positive impact on the expectation of new proposals [50]. Duncan and Weiss [51] describe the learning capabilities of the firm as "the process by which knowledge about action-outcome relationships and the effects of the environment on these relationships are developed." Failure to invest in learning can increase the likelihood of a standard being locked out [14]. Thus, the *learning orientation* of the group of standard supporters plays a major role in standard dominance.

A standard support strategy contains the range of strategies adopted in a market to win a standards battle. The *appropriability strategy* refers to an actor's ability to capture profits generated by a standard [41]. One method to accomplish this is via the organization's intellectual property rights. An open licensing policy encourages imitation by competitors, which will, in general, increase the chances of a standard becoming dominant [20]. However, following this strategy, the firm itself will often reap lower benefits from the standard [52]. *Timing of entry* of the first products in which the standard is used can be essential for achieving dominance in the market [53]. It is particularly important if there is a clear market need for a standard, without a preference for a certain standard [1]. Schilling [14] studies several product categories, including PC operating software and video game hardware, and tests the relationship between timing of entry and the chances of standards being locked out of the market. The conclusion is that there is a U-shaped relationship with the likelihood of technological lockout [13], [14]. Christensen *et al*. [54] come to a similar conclusion and show that there is a "window of opportunity" for optimally entering the market. Customer expectations play an important role in standards battles [5] and, therefore, *marketing communications* are important to gain more market share. In the early phase of a battle, preannouncements can be used to discourage users from buying rivals' designs prior to the introduction of one's own [55], [56]. Also, free trials may be offered to increase installed base [57]. At later stages, marketing communications such as online advertising, word-of-mouth advertising or public relations campaigns are important.

IV. Methodology

A. Fuzzy AHP

Decision makers confronted with difficult multicriteria choices (e.g., which standard should be supported) might prefer a simple method to decrease complexity [23]. Decision makers are unable to examine even a small number of criteria or alternatives at the same time [58]. Saaty [59] therefore states that "the decision-making process should be mathematically rigorous and operationally simple and transparent to the decision maker." The AHP method is a suitable approach that makes use of simple scoring questions to derive judgments for criteria. It is used in multiattribute utility models to derive the optimal decision to a problem when multiple criteria have to be taken into consideration [34], [60]. Since relative ratios of weights of importance can more easily be provided by decision makers than absolute weights [61], the method ascribes a relative importance to both the criteria and the alternatives by comparing those decision elements in pairs.

The AHP is especially suited to tackle complex decision problems [62] because it can structure these complex problems by hierarchically decomposing complex factors [63], [64]. Furthermore, the method is appropriate for addressing events that are affected by tangible and intangible qualitative criteria [63], [65]. Another advantage of the method is that it allows for and measures judgment inconsistencies which will inevitably occur when comparisons are made through individual subjective judgments [66]. In this respect, the AHP method is appropriate for standard selection since the choice of a standard is complex because the categories of factors for standard dominance include both tangible factors such as financial strength of the standard supporter and intangible factors such as its reputation. Finally, in the situation of selecting standards, judgments will inevitably be somewhat subjective and thus prone to inconsistency. For example, judgments might be subjective because they are influenced by prior experience in past standards battles.

Some previous studies [59], [67] describe the AHP and its applications in detail. The most challenging step of this methodology involves quantifying the expert judgment using crisp ratios. This makes the methodology inefficient when it comes to dealing with imprecise knowledge and judgments provided by experts/decision makers. To overcome this inefficiency,

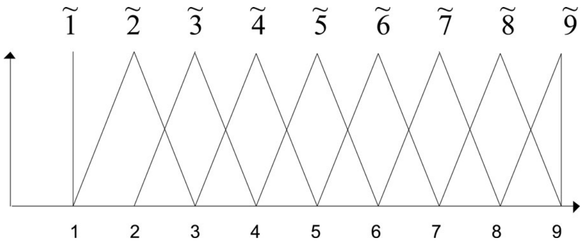

Fig. 2. Triangular fuzzy numbers.

van Laarhoven and Pedrycz [68] proposed fuzzy AHP, as a fuzzy extension of AHP. This was extended by other authors (e.g., [69]–[74]). However, even using these fuzzy AHPs, the challenging issue of "consistency" remained unsolved. Recently, Mikhailov [75] proposed a fuzzy preference programming to derive the priority vector in fuzzy AHP, which provides a well-interpretive consistency index. This methodology was improved by Wang and Chin [76]. In the next section, we describe Mikhailov's fuzzy AHP improved by Wang and Chin [76].

B. Fuzzy AHP Using Fuzzy Preference Programming

In this section, we describe the procedure of fuzzy AHP [75], [76]. First, we need to construct a hierarchy (first level: goal; second level[2]: criteria; third level: alternatives). Then, extracting the knowledge of experts/decision makers, we compare the criteria and alternatives in a pairwise fashion, which provides the comparison matrices as follows:

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{bmatrix} \tag{1}$$

where $\tilde{a}_{ij}$ is a triangular fuzzy number (TFN) to show the decision maker/expert's preference of i over j and $\tilde{a}_{ji} = 1/\tilde{a}_{ij}$. Here, we present the definition of TFN and their operational laws.

Definition 1: [68] TFN: A fuzzy number N on $\Re$ is defined to be a TFN if its membership function $\mu_N(x) : \Re \rightarrow [0,1]$ be

$$\mu_N(x) = \begin{cases} \dfrac{x-1}{m-1}, & l \le x \le m, \\ \dfrac{u-x}{u-m}, & m \le x \le u, \\ 0, & \text{otherwise}, \end{cases} \tag{2}$$

where l and u are the lower and upper bounds of the support N, respectively, and m is the modal value. This TFN can be noted by the triple (*l,m,u*). We use the following TFNs for the comparisons (see Fig. 2).

According to [75], the decision maker provides at most $n(n-1)/2$ pairwise comparisons $\tilde{a}_{ij}, i = 1, 2, \ldots, n-1,\ j = 2, 3, \ldots, n, j > i$.

[2]In some cases, more than one level is constructed for criteria where a subhierarchy of criteria exists.

To derive a crisp priority vector $w = (w_1, w_2, \ldots, w_n)^T$, Mikhailov [75] proposed a fuzzy prioritization programming as follows.

The goal is to determine the relative weight of the criteria $w = (w_1, w_2, \ldots, w_n)^T$ such that the ratios w_i/w_j are approximately within the scopes of the pairwise judgment $\tilde{a}_{ij}$ which means $l_{ij} \tilde{\le} w_i/w_j \tilde{\le} u_{ij}$.

For each i and j, many w_i and w_j may satisfy the aforementioned inequality. However, different ratios w_i/w_j provide a different degree of satisfaction for the decision maker/expert. The satisfaction of the decision maker/expert may be measured by a membership function as:

$$\mu_{ij}\left(\frac{w_i}{w_j}\right) = \begin{cases} \dfrac{\frac{w_i}{w_j} - l_{ij}}{m_{ij} - l_{ij}} & \dfrac{w_i}{w_j} \le m_{ij}, \\ \dfrac{u_{ij} - \frac{w_i}{w_j}}{u_{ij} - w_{ij}} & \dfrac{w_i}{w_j} \ge m_{ij}. \end{cases} \tag{3}$$

The membership function (3) may take the following values:

$$\mu_{ij}\left(\frac{w_i}{w_j}\right) \in (-\infty, 0), \quad \text{if } \frac{w_i}{w_j} < l_{ij} \text{ or } \frac{w_i}{w_j} > u_{ij} \tag{4}$$

$$\mu_{ij}\left(\frac{w_i}{w_j}\right) \in [0, 1], \quad \text{if } l_{ij} \le \frac{w_i}{w_j} \le u_{ij} \tag{5}$$

and takes the maximum value of 1 when $\frac{w_i}{w_j} = m_{ij}$. The fuzzy preference programming is aimed at finding the optimal crisp priority vector w^* of the fuzzy feasible area P on the (n–1)-dimensional simplex Q^{n-1}

$$Q^{n-1} = \left\{ w_i \,\middle|\, \sum\nolimits_{i=1}^{n} w_i = 1, w_i > 0 \right\}. \tag{6}$$

With the following membership function:

$$\mu_P(w) = \min_{ij} \{\mu_{ij}(w) \,|\, i = 1, 2, \ldots, n-1, \quad j = 2, 3, \ldots, n, j > i\}. \tag{7}$$

There is always an optimal crisp priority vector with the maximum degree of membership as follows:

$$\lambda^* = \mu_P(w^*) = \max_{w \in Q^{n-1}} \min_{ij} \{\mu_{ij}(w)\}. \tag{8}$$

Problem (8) can be transformed to the following problem:

$$\begin{aligned} &\max \lambda \\ &\text{s.t.} \\ &(m_{ij} - l_{ij})\lambda w_j - w_i + l_{ij} w_j \le 0, \\ &(u_{ij} - m_{ij})\lambda w_j + w_i - u_{ij} w_j \le 0, \\ &\sum\nolimits_{k=1}^{n} w_k = 1, \\ &w_k > 0, \\ &i = 1, \ldots, n-1, \ \ j = 2, \ldots, n, \ \ j > i, \ \ k = 1, \ldots, n. \end{aligned} \tag{9}$$

By solving the above nonlinear programming problem, we can obtain the optimal priority vector $w^*$and λ^*. However, by using (9), the decision maker/expert's maximum satisfaction

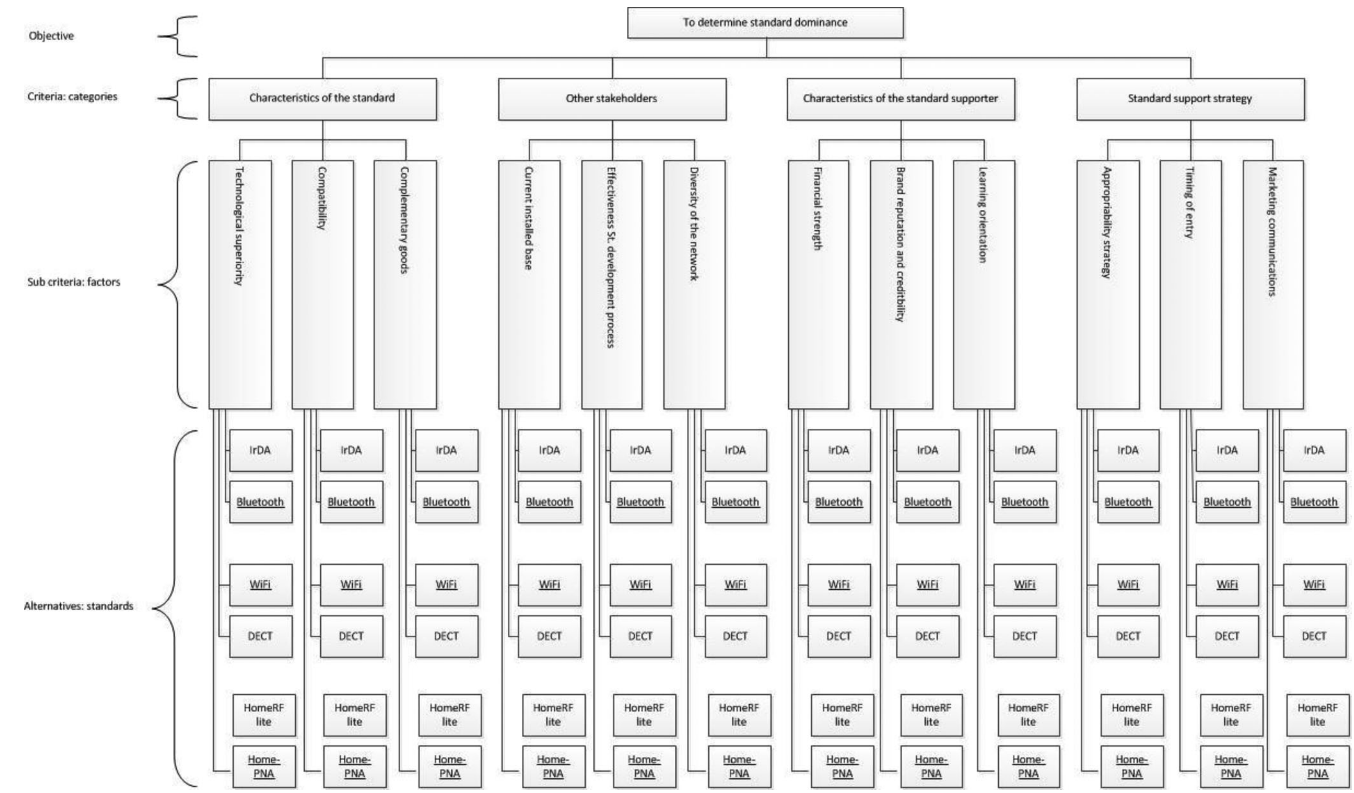

Fig. 3. Decision hierarchy.

(λ^*) may be obtained negative. To avoid this problem, Wang and Chin [76] modified (9), and proposed the following prioritization problem:

$$\text{Min } J = (1-\lambda)^2 + M \sum_{i-1}^{n-1} \sum_{j=i+1}^{n} \left(\delta_{ij}^2 + \eta_{ij}^2\right)$$

s.t.

$$x_i - x_j - \lambda \ln(m_{ij}/l_{ij}) + \delta_{ij} \ge \ln l_{ij},\ i = 1,\dots,n-1,\quad j = i+1,\dots,n,$$

$$-x_i + x_j - \lambda \ln(u_{ij}/m_{ij}) + \eta_{ij} \ge -\ln u_{ij},\quad i = 1,\dots,n-1,\ j = i+1,\dots,n,$$

$$\lambda, x_i \ge 0,\ i = 1,\dots,n,\ \delta_{ij}, \eta_{ij} \ge 0,\ i = 1,\dots,n-1,\quad j = i+1,\dots,n, \tag{10}$$

where $x_i = \ln(w_i)$ and M is a large constant such as 10^3. $\delta_{ij} + \eta_{ij}$ are nonnegative deviation variables to avoid λ from taking negative values. As $x_i = \ln(w_i)$, having x_i^*, we can simply calculate the optimal weights as follows:

$$w_i^* = \frac{\exp(x_i^*)}{\sum_{j=1}^{n} \exp\left(x_j^*\right)} \quad i = 1,\dots,n. \tag{11}$$

We used the fuzzy AHP to determine weights for the factors in the framework presented in Section III. Furthermore, by analyzing three standards battles, we examined whether our framework can help to determine a winning standard, and whether this standard was similar to the one that actually won the battle.

As mentioned before, the first step in the fuzzy AHP is to structure the decision problem into a decision hierarchy of objective, (sub)criteria, and alternatives: "A problem well structured is a problem half solved" [38]. In our case, the decision hierarchy consists of four levels (see Fig. 3). The first level consists of the objective of the decision problem. The categories and factors of the framework presented in Section III are used to develop the second and third levels of the hierarchy. The fourth level consists of three groups of standards. Each group comprises two compatibility standards that competed in historical standards battles. The outcome of these battles is known as one standard has already reached dominance. An independent panel of both practitioners and academics was formed to confirm the dominant standard. This panel of experts did not participate in the AHP study. We also gathered secondary data for each standards battle by analyzing the press releases of the actors involved, several online news archives including ABI-inform, and other online sources that report on the standards. The winning standards are underlined in Figs. 3 and 4. The first standards battle, for short-range wireless communication, was between infrared data association's wireless specifications (IrDA) and Bluetooth. Bluetooth became dominant. In the second battle, for mid-range wireless data communication, WiFi competed with DECT. WiFi won the battle. The third standards battle, for home networking, was between HomeRF Lite and HomePNA. The latter achieved dominance.

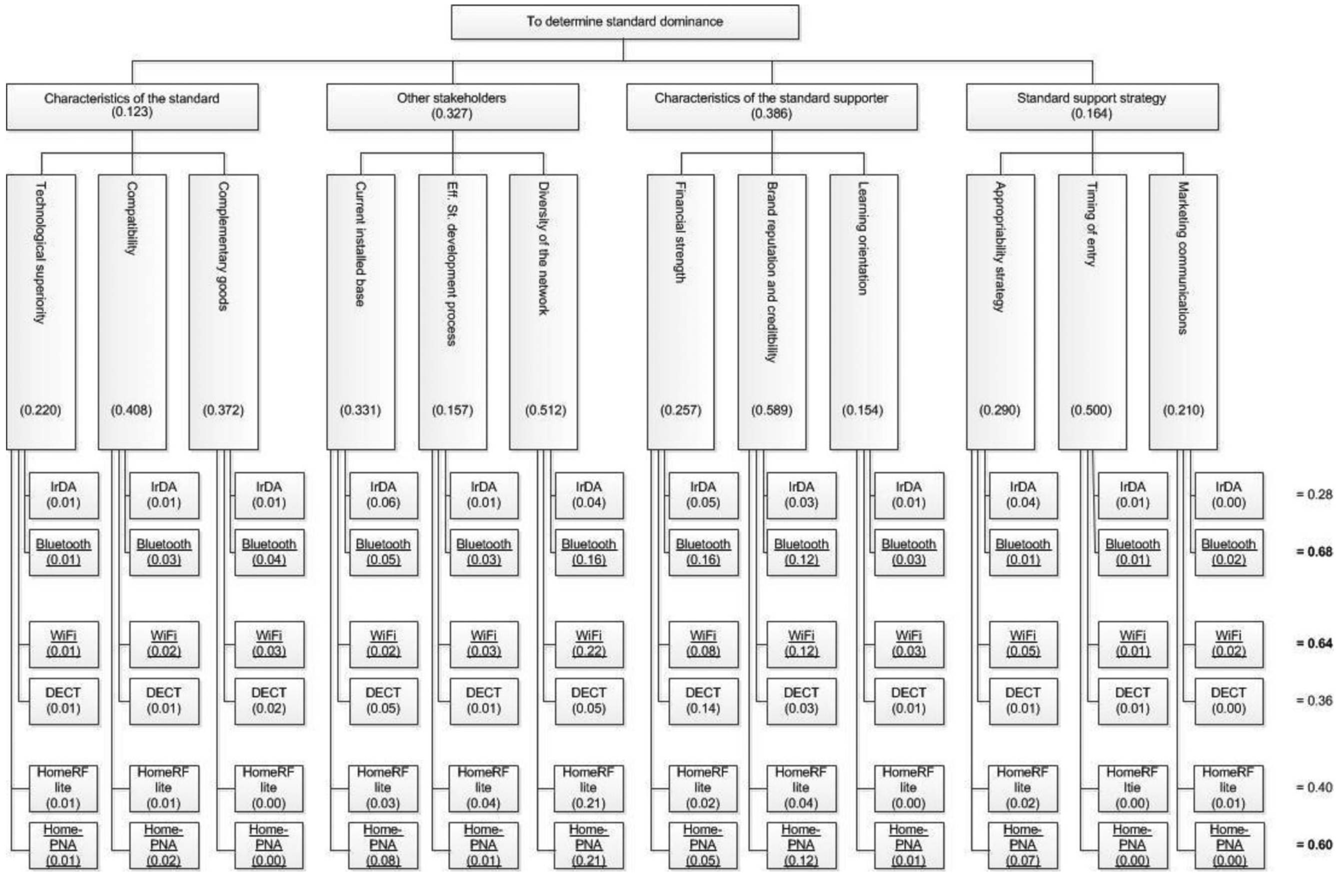

Fig. 4. Results.

C. Data Collection and Analysis

Questionnaires were developed for the levels in the decision hierarchy. One questionnaire was developed in which the categories and factors were compared in pairs. We conducted ten structured interviews with standardization experts that are active in various industries including telecommunications and information technology (different from the members of the panel mentioned above). Interviews with experts lasted for about 2 hours. In each interview, the respondents were asked to compare the categories and factors (in pairs). They were asked: "How much more strongly does category/factor A influence the chances that a particular standard reaches dominance compared to category/factor B?" The objective of each interview was to establish weights for the categories and factors for standard dominance. We also developed three questionnaires (one for each standards battle) and asked respondents to rate the standards on how they score on each factor. We took 2003 as reference point for all three battles because the standards coexisted in that year. For example, respondents were asked: "In 2003, how much more compatibility did standard A guarantee compared to standard B?" We conducted interviews with three of the ten standardization experts who were familiar with each of the standards. These interviews lasted for about 4 hours. To guarantee the validity of each questionnaire, the framing of each question was carefully chosen such that it reflected the relation between levels [24].

When multiple participants are interviewed, priorities can be set by consensus, vote or compromise, mean of individual judgment, and separate models or parts of models can be used [64], [77] whereby participants enter their judgment into a separate model, which is then averaged into one collective model [78]. We use separate models. In our study, the opinions of the participants are considered to be equal in importance. Consequently, the opinions of the experts receive equal weighing when aggregating the judgments. Following Ramanathan [79], we applied the weighted arithmetic mean method for the aggregation. This has often been done in prior studies where multiple independent respondents are interviewed [80], [81].

V. Results

The weights for the categories and underlying factors that influence the chances that standards achieve dominance are presented in Fig. 4. The respondents indicated that "characteristics of the standard" was the least important category (0.123). The categories "other stakeholders" and "characteristics of the standard supporter" both have relatively high weights (0.327 and 0.386) indicating that the respondents judged these two categories to be important. Finally, the "standard support strategy" was considered to be less important (0.164). Thus, it appears that the dominance of the group of standard supporters, as well as other stakeholders, play an important role. Both the superiority of the standard and the strategy of the standard supporter are judged to be less important compared to the other categories of factors.

Within the category "characteristics of the standard," the technological superiority of the standard was judged to be the least important factor (0.220). The other two factors in this category were judged to be more important. This is supported in the literature, where it is argued that the superior standard will not necessarily become dominant [26]. So, a standard does not necessarily have to be technologically superior. In the "other stakeholders" category, the respondents judged the diversity of the network of actors to be the most important factor (0.512), more important than the actual installed base of the standard (0.331) and the effectiveness of the standard development process (0.157). Apparently, it is imperative to ensure that a diverse set of actors supports the standard. Indeed, in networks that are diverse, firms will have access to more diverse information [82], which leads to greater levels of learning [83], and complementary technological capabilities can be matched [84]. Additionally, when the network of the standard includes diverse actors, the potential installed base of the standard increases as it can make use of the installed base of all the actors involved. Within the category "characteristics of the standard supporter," the experts judged brand reputation and credibility of the standard supporter to be the most important factor (0.589). Apparently, financial strength (0.257) is less important. Whether an actor invests in learning or not was rated as the least important factor (0.154). Finally, in the "standard support strategy" category, the experts judged the timing of entry to be the most important factor (0.500). There are ample studies that emphasize the importance of timing of entry [13], [14].

From the data, it appears that factors for standard dominance are not equally important. In each category, one or two factors appear to be more important than other factors. Global weights for each factor should reflect these differences in importance. To obtain these weights, we multiplied the weights of the categories by the weights of the underlying factors. The results are presented in Table I. It appears that the diversity of the group of standard supporters is the most important factor and that the brand reputation and credibility of the firm are especially important. Prior research also emphasizes the importance of this factor, where it is argued that a group of standard supporters with a good reputation will find it easier to attract other stakeholders to join the group [42] resulting in an increase in the standard's installed base.

For each group of standards, we analyzed which standard has the highest chance of achieving dominance. Three respondents were asked to rate each standard on the 12 factors. The results are presented in the last level of the decision hierarchy in Fig. 4. The data include the chances (in weights) that a standard reaches dominance. In the group of short-range wireless communication standards, the total score on each factor for Bluetooth is 0.68, whereas the total score for IrDA is 0.28. In the group of the mid-range wireless communication standards, WiFi achieves 0.64 compared to 0.36 for DECT. Finally, in the group of standards for home networking, the total score for HomePNA is 0.60, whereas HomeRF Lite is 0.40. When the data from the AHP study are compared with the actual success of the standard, we observe that the actual outcome of each of the three standards battles studied in the paper is identical to the outcome as suggested by the AHP method. Apparently, by using the Fuzzy AHP, the experts could determine the winning standard in each of the battles.

TABLE I
FACTORS FOR STANDARD DOMINANCE RANKED BY IMPORTANCE

Factor	Avg. weight
Diversity of the network	0.1897
Brand reputation and credibility	0.1825
Financial strength	0.1159
Current installed base	0.0904
Timing of entry	0.0874
Compatibility	0.0685
Complementary goods	0.0542
Marketing communications	0.0442
Technological superiority	0.0437
Effectiveness of the standard development process	0.0424
Appropriability strategy	0.0422
Learning orientation	0.0398

VI. DISCUSSION AND CONCLUSION

In this study, we provide a first indication that the framework of factors combined with the use of the fuzzy AHP can be used to explain the outcome of standards battles and to support decision making related to such battles. Thus, this study provides empirical evidence for the notion that the outcome of standards battles is not fully characterized by path dependency but that factors for standard dominance can be determined. We show that it is possible to model the process of standard selection, and provide a first indication of the relative weights of the factors and, by doing so, we contribute to the empirical literature on standardization.

We have applied a decision-making approach, the fuzzy AHP using fuzzy preference programming, to standard selection, bridging the literature on decision theory and standardization. This study provides evidence that the improved fuzzy AHP methodology developed by Wang and Chin [76] can be successfully used. The AHP method has been applied in many research areas and for many applications [85]. However, to our knowledge, this is the first study to apply the AHP for a standardization problem.

TABLE II
APPLYING THE DECISION MODEL TO NINE CASES OF STANDARDS BATTLES AS REPORTED IN THE LITERATURE

	Standards battle	VCR [11].	Microprocessors [87, 88].	Analog cellular mobile telecom [90].	Video gaming consoles (3rd generation) [32, 89].	Video gaming consoles (4th generation) [32, 89].	Digital cellular mobile telecom [90].	Video gaming consoles (5th generation) [32, 89].	Video gaming consoles (6th generation) [32, 89].	Blue laser DVDs [10, 99].
	Year of introduction first standard	1975	1980	1981	1986	1989	1992	1995	1999	2002
	Competing standards (Winner in bold)	**-VHS** -Betamax -V2000	**-RISC** -CISC	**-AMPS/TACS** -NMT	**-NES** -Master System -Atari 7800	**-Sega Genesis** -NEC TurboGrafx-16 -Nintendo SNES	**-GSM** -DAMPS -PDC -PHS -CDMAOne -PACS	-Interactive Multiplayer -Atari Jaguar -Sega Saturn **-PlayStation** -Nintendo 64	-Dreamcast **-PlayStation 2** -GameCube -Xbox	**-Blu-ray** -HD DVD
	Characteristics of the standard									
1	Technological superiority	■	■		■			■	■	■
2	Compatibility				■	■			■	■
3	Complementary goods	■	■		■	■		■	■	■
	Other stakeholders									
4	Current installed base	■	■	■	■	■		■	■	■
5	Eff. standard development Process		■	■			■			
6	Diversity of the network	■	■		■	■	■	■	■	■
	Characteristics of the standard supporter									
7	Financial strength								■	■
8	Brand reputation and credibility	■	■		■	■		■	■	
9	Learning orientation	■						■	■	
	Standard support strategy									
10	Appropriability strategy		■	■	■	■	■		■	
11	Timing of entry	■			■	■	■		■	■
12	Marketing communications				■	■		■	■	■

A. Model Accuracy and Applicability

In the literature, it is argued that MCDM processes should be embedded in a wider process of problem structuring where objectives, criteria, and alternatives are explored [38]. This study attempts to do so by conducting a literature review and providing a comprehensive set of factors for standard dominance. An important question is how closely the results of the fuzzy AHP match the real decision made [24]. Most studies that use the AHP or fuzzy AHP do not include a comparison with the decision actually made. In this study, we make this comparison and observe that the actual outcome of each of the three standards battles studied in the paper resembles the outcome as suggested by the AHP method. This serves as proof of the legitimacy of AHP as a tool for decision making, and is a first indication of the decision model's accuracy and applicability.

To further test the accuracy and applicability of the decision model, we applied it to nine cases of standards battles described in the literature. We chose diverse battles that were fought in different time periods (1975–2008), across various industries (information technology, consumer electronics, telecommunications, etc.), and in different locations (U.S., Europe, and Japan). Table II provides an overview of the factors from our model that were applicable in the case studies analyzed in the literature. A supplemental file in which the cases are further explained is available. In every standards battle that we studied, we observe that the factors mentioned in the model determine its outcome.

The classical battle for the VCR was waged in the 1970s and 1980s. VHS and Betamax were introduced earlier than V2000, which partly resulted in the failure of V2000 [11]. VHS eventually won the standards battle. One of the reasons behind the triumph of VHS over Betamax was that JVC followed a strategy aimed at forming a large diverse network of manufacturers of VCR systems that implemented the VHS standard. Thus, JVC had access to a larger range of manufacturers of complementary goods than Sony [11] and the manufacturers also offered a more diverse range of VHS devices [86]. A similar phenomenon can be observed in the battle between RISC and CISC microprocessor architectures which was eventually won by Sun's RISC-based SPARC standard [87]. Vanhaverbeke [88] observed that the RISC alliance network was more diverse in terms of the complementary capabilities of different firms that were included in the network. This also positively affected credibility for the RISC standards among potential users.

From 1976 to the present, multiple standards battles were fought for different generations of home video game consoles. In the third generation (1986–1990), Sega's Master System was technologically superior, but Nintendo spent more on marketing and offered a wider range of complementary products in the form of games, partly leading to Nintendo's NES' dominance. Nintendo also followed an aggressive appropriability strategy whereby third party developers could produce a maximum of five games per year for NES, which increased the quality of available games on the market [32], [89]. Later, in the fourth generation, Sega followed a less restrictive appropriability strategy compared to Nintendo and increased the number of complementary goods available for its Genesis system, partly leading to its dominance over Nintendo. In the fifth generation video console standards battle, the early success of the Nintendo 64 console can partly be attributed to the availability of complementary goods; the console was bundled with the popular game Super Mario 64 [32]. Also, the Nintendo 64 system was announced more than 2 years before it actually became available [32]. These preannouncements (a form of marketing communications) increased installed base and discouraged users from adopting rivals' standards. PlayStation eventually won the war because it also targeted young males instead of only early teens. In the sixth generation video console standards battle, Microsoft (Xbox) was a newcomer in the industry and had no experience compared to its competitors. Also, Sony made its PlayStation 2 backward compatible with PlayStation which allowed users to play their old PlayStation games, effectively increasing the installed base for PlayStation 2 [89].

At the beginning of the 21th century, HD-DVD and Blu-ray competed to become the dominant standard for storing high definition video content on optical discs. The standards were not only implemented in high definition DVD players but also in PCs and video gaming consoles, thereby creating a larger overall installed base [10]. Also, the Blu-ray disc association used its financial resources to attract Warner, an important manufacturer of complementary goods. This was the turning point in the battle. Many companies followed Warner and switched from HD-DVD to Blu-ray, eventually leading to its dominance.

In the 1980s, the standards battle for analog cellular mobile telecommunications was fought. The success of AMPS/TACS and NMT can partly be attributed to their level of openness; the competing standards from Japan, Germany, France, and Italy were closed [90]. In 1995, GSM's success in the digital cellular mobile telecommunications industry was, in part, due to the effectiveness of the standard development process, which constituted both firms and national governments, and led to open standards and an initial installed base [90].

To conclude, the outcome of each of these standards battles can be explained by making use of the factors from our model. This serves as an additional test of the model's accuracy and applicability. We notice that the important factors that were derived from the analysis in this paper, such as diversity of the network and brand reputation and credibility, also contribute to standard dominance in most of the cases that we studied. However, some factors from our model are not mentioned in specific cases. Not all factors apply in every case study. For instance, backward compatibility does not apply when there is no previous generation of technology. Some factors might not have been mentioned because the researcher may not have been aware of all the factors.

B. Limitations and Recommendations for Further Research

Saaty [91] has studied the integration of judgment into actual decision making and, although he assumes that the judgments that are derived from the decision maker represent the actual decision, other authors [35] show that there is a difference between judgment and choice. In the AHP, respondents are asked to judge the importance of different elements in a hierarchy. However, this does not necessarily mean that they will also choose one element over another element when the actual decision has to be made. In this study, we follow Saaty [91] and assume that judgments represent decisions. However, in the descriptive approach to decision making this could be seen as a limitation.

Although the panel of experts that confirmed the dominant standard did not participate in the AHP study, the experts that did participate might have been biased as they could have known the outcome of the standards battles. This creates a risk of common method bias, which is an important limitation in this study. We have reduced this risk by asking respondents to imagine themselves in the 2003 situation and to answer the questions without taking into account their current knowledge about later developments in the standards battles, including the outcome of these battles. As we observed that the losing standards were rated better on some factors compared to the winning standards, the outcome of the standards battle did not fully determine the judgments of the respondents. Future longitudinal research could study current standards battles and validate whether the framework of factors proposed in this study can be used to predict the chances that a standard will achieve dominance by applying the AHP. Then, after some years, it could be possible to assess the extent to which the results of the AHP match the real "decisions" finally made in the market.

Apart from this limitation, we note that there are important differences between MCDM approaches and statistical approaches—the dominant approaches in social sciences—in terms of their objectives, applicability, and data set limitations. For instance, while the main objective of a variety of statistical approaches is to find the relationship between different constructs of a model, the main objective of MCDM methods is to model and solve the complex problems in such a way that they are easier to understand for practitioners and decision makers. In other words, while statistical methods are descriptive in nature, MCDM methods are normative. Statistical methods usually need a considerable number of observations, while MCDM methods can find the best alternatives using a limited number of data. So, while the reliability of the results obtained from the statistical approaches may largely depend on the number of observations, the results obtained from MCDM methods are judged to be reliable if other criteria are satisfied. For example, if the results obtained by the MCDM method are close to the real-world situation, they are judged to be reliable. Research has shown the robustness of the MCDM used in this paper (AHP). Saaty [92] and others (e.g., [93], [94]) have studied the validity of the AHP investigating several real-world problems and have shown that AHP can produce very reliable results even based on the opinion of two experts. These studies compare the predicted results obtained by AHP and the actual events that happened afterward in the real world. For example, Saaty and Khouja [95], as two experts, used their knowledge to find the relative influence and standing of seven different countries in the world without looking at their gross national product (GNP). The relative influence they found using AHP was very close to the relative GNP values. Others have found the same robustness for fuzzy AHP using analytical and statistical tests (e.g., [96], [97]).

A last limitation is that we focused on compatibility standards. While this is certainly an important type of standard, several other categories of standards exist. Such standards may also compete for acceptance. Future research might reveal whether similar factors determine the outcome of such battles.

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