

Success factors for standards during the technology life cycle

van de Kaa, Geerten; de Vries, Henk J.

DOI

[10.1016/j.csi.2025.104043](https://doi.org/10.1016/j.csi.2025.104043)

Publication date

2025

Document Version

Final published version

Published in

Computer Standards and Interfaces

Citation (APA)

van de Kaa, G., & de Vries, H. J. (2025). Success factors for standards during the technology life cycle. *Computer Standards and Interfaces*, 95, Article 104043. <https://doi.org/10.1016/j.csi.2025.104043>

Important note

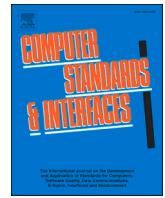
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.



Success factors for standards during the technology life cycle

Geerten van de Kaa^{a,*}, Henk J. de Vries^{a,b}

^a Faculty of Technology, Policy, and Management, Delft University of Technology, Jaffalaan 5, 2628BX, Delft, the Netherlands

^b Rotterdam School of Management, Erasmus University, Burgemeester Oudlaan 50, 3062 PA Rotterdam, the Netherlands

ARTICLE INFO

Keywords:

Standards battles
Standardization
Technology life cycle
BWM
Best Worst Method

ABSTRACT

Technological developments such as the Internet of Things, and artificial intelligence result in new innovative systems. In these systems, ICT is integrated in products, services and processes. Interconnectivity gets crucial and standards should facilitate this. New standards complement existing ones and these may originate both from the ICT field and from other fields. These fields have different standardization cultures and often, multiple standards are competing. The question is which standard, if any, will achieve market success. We relate the success factors to the different phases of the technology life cycle. We assess the importance of these factors by using the Best Worst Method. In the discussion section, we argue how the importance of certain factors may change and which new factors pop up in an increasingly globalized and digital world. This should provide a basis for future research on market success of standards in this new context.

1. Introduction

Many systems consist of elements produced by different firms that need to be interoperable. Compatibility standards enable this. In many cases, there is not just one standard but different standards compete for market acceptance. For investment decisions, it is important to know which one is expected to win. In most cases, one standard turns out to become dominant. The reason is that standards-based markets are often characterized by increasing returns to adoption. Due to market mechanisms, such as indirect and direct network externalities [1,2], the standard that has an initial lead in installed base attracts more users and becomes dominant [3,4].

Companies that sell products in which the winning standards are applied have a huge competitive advantage compared to companies whose product specifications meet a losing standard. That is why, often, fierce ‘standards battles’ are fought in these markets [5,6].

Various technology management scholars have studied such battles including, e.g., VHS vs Betamax [7,8] and Blu-ray vs HD-DVD [5,9]. They attempt to explain the outcome of these battles by defining factors that affect the build-up of an installed base [10–13]. However, these scholars predominantly focus on the period from the initial introduction of the first product in which the standard has been implemented until one of the competing standards has achieved dominance. Yet, this dominance process involves other phases before and after this phase that have received relatively little attention. For example, before the first

product in which the standard is implemented is introduced in the market, prototypes of that product may have been developed, and after standard dominance ‘within-standard competition’ takes place: competition between companies using the same standard.

Products are shaped by standards and companies develop, produce, market and sell these products. Therefore, factors for success in standards battles relate not only to the standard itself but also to the products for which it is used and to the companies designing, producing, marketing, selling or using these products. Success of the standard is related to the success of these products and the success of these companies, the causality is in both directions. The focus of this paper is on success factors for standards.

The research question of this paper is: what is the importance of factors for standard dominance during each phase of the technology dominance process as defined by Suarez [12]? We apply the BWM method to structure expert opinions [14,15].

The paper contributes to the literature on standards by assigning weights to factors for standard dominance in each phase of the dominance process as defined by Suarez [12]. It shows how companies can influence the outcome of standards battles to their advantage.

2. Theory

The processes and mechanisms that lead to single de-facto standards or dominant designs has been studied by numerous scholars from a

* Corresponding author.

E-mail addresses: g.vandekaa@tudelft.nl (G. van de Kaa), hvries@rsm.nl (H.J. de Vries).

diverse range of backgrounds. Evolutionary economists tend to believe that standards get established in the market after a period of radical change and experimentation which is referred to as the fluid phase [16, 17]. After the dominant standard has been set, the era of incremental change sets in. They argue that technological change is cyclical and technological discontinuities will emerge eventually resulting in a period of radical change and the establishment of a dominant standard [18]. These scholars argue that firms cannot influence the outcome of the standards battle per se, and the technological discontinuity does not necessarily result in a dominant standard in the industry [19].

In the 1980s, industrial economists and network economists have explored the notion of network externalities; a mechanism that results in products (in which standards are implemented) increasing in value the more they are being adopted by users [1,2]. For example, the value of a mobile phone to users when it is not part of a mobile telecommunications network is equal to its technological stand-alone value. When it becomes part of a mobile network, users can call other users, and the value of the mobile phone system will increase by a factor of $\frac{1}{n}(n-1)$, n being the number of users that can be reached thanks to having adopted the same mobile telecommunication standard. Network economists have come up with factors for standard dominance, such as installed base, and various factors that can influence the installed base, such as setting low prices for products in which the standards are incorporated (penetration pricing) [20].

Technology management scholars have studied various examples of standards battles and have investigated whether it is possible to explain and even predict their outcome [10,11,21,22]. They borrowed the idea from network economists that a large installed base is crucial for setting dominant standards, and they have explored ways of increasing the installed base [3]. By, for instance, applying fierce marketing campaigns, the expected and anticipated installed base can be positively influenced [23]. And as expectations count for a lot in standards battles [4], these subjective components of installed base affect actual installed base positively [23]. Other scholars point to the importance of following an open standards strategy [24,25]. This basically entails that patents are applied as few as possible in standards so the cost of applying the standards in products decreases. This enhances the chances of standard dominance, as in the case of Sun's Java standard programming language [24]. Suarez [12] distinguishes between five phases of the technology dominance process. The first phase, R&D buildup, starts with research and development. According to Suarez, this can be seen as the start of the 'technological field'. A new phase, Technological feasibility, starts when the first working prototype has been developed. The third phase, Creating the market, starts with the launch of the first commercial product (in which the standard is implemented). The fourth phase, Decisive battle, starts when 'an early front runner' emerges. The final phase, Post-dominance, starts when a standard has achieved dominance [12].

Standardization scholars distinguish between market-based, committee-based, and government-based standardization [26]. Many scholars study market-based standardization and investigate standards battles. They have mainly focused on explaining and predicting standard dominance in the fourth phase; the actual standards battle [5,6,27,28]. They have developed frameworks consisting of factors for standard success [10,12,29] and they have applied these factors to various cases [5,6,21,30]. The framework developed by van de Kaa et al. is one of the most complete frameworks. However, this framework needs to be connected to the phases distinguished by Suarez [12]. This was done before by Den Uijl [31] on a slightly different set of factors and based on several cases, and recently by others [32,33]. However, in this study, we apply a systematic approach and assign weights to the factors. We focus on the firm-level factors from van de Kaa's model, as companies can directly influence these factors.

The studies that are discussed up until now focus on how companies can ensure that their standard is successful given market mechanisms. Researchers have also looked at the reasons why companies adopt standards [34]. These researchers often use literature on innovation

adoption to look at the benefits that the standard offers [35]. Furthermore, scholars have borrowed from neo-institutional theory to argue that companies adopt standards because, e.g., others do so [36].

3. Method

In order to determine the importance of factors for standard success per phase of the dominance process, two studies were conducted. The first study determines the factors for standard dominance during the subsequent phases, using both primary and secondary sources, while the second study estimates the importance of these factors using primary sources. Primary sources include three expert interviews. Details about the interviewees can be found in Table 1.

Secondary sources include literature that was arrived at by forward searching two key papers that report on factors for standard dominance: van de Kaa et al. [13] and Suarez [12]. The abstracts of the papers that were found were scanned and, when deemed relevant, further analyzed. Papers were selected when they focus on factors for standard or design dominance in one or more stages of the technology dominance process as defined by Suarez [12]. Example papers include, Bakker, van Lente and Meeus [37] who have studied factors for design dominance in the second stage and van de Kaa et al. [38], who have focused on factors for standard dominance in the fourth stage.

The primary source used in study 1 included an interview with an expert (expert 1 in Table 1) who has comprehensive knowledge on standards battles. He has detailed knowledge about the topic under investigation; standard dominance factors per phase of the technology dominance process. A factor is considered relevant in this research if it is found in the literature or if the factor is mentioned to be relevant by the interviewee.

The methodology used to analyse the relevant factors and determine their corresponding weight is the best-worst method (BWM) developed by Rezaei [14,15]. This is a multi-criteria decision making (MCDM) method that uses pairwise comparison to effectively compare criteria. It has been successfully applied to non-standardisation cases such as airline baggage handling systems [39] and offshore outsourcing adoption [40]. Compared to other commonly used methods for establishing weights in an MCDM problem, such as Analytic Hierarchy Process (AHP), the BWM requires less comparison data whilst still deriving highly reliable weights [14]. Therefore, BWM is chosen as the method for this research, as the number of interview candidates with thorough knowledge on this topic is very limited.

Three experts (see Table 1) were asked to rank the factors on importance by means of a questionnaire. The factors were clustered into four categories derived from the framework of van de Kaa et al. [13]. The respondents were asked to first rank these four categories by means of pair-wise comparison, resulting in weights of the categories. Then they were asked to make pair-wise comparisons for the factors within the four categories, resulting in the local weights. By multiplying the local weights of the factors with the weight of its corresponding category, the global weights of the factors were obtained. This process was repeated for each phase of the dominance process as defined by Suarez [12]. A more detailed overview of the steps involved in the method is discussed below.

To arrive at the weights of factors (and cluster of factors) per stage of the technology dominance process the following steps (that are part of a typical BWM study) were taken [14,15]:

1. The relevant factor (denoted by c_j , $j = 1, \dots, n$) were identified by screening the literature and interviewing a key expert.

Table 1
Background, position, and expertise of respondents.

#	Background	Position	Expertise
1	Academia	Professor	Management and standardization
2	Academia	Researcher	Standardization processes
3	Academia	Researcher	IT standardization

2. The most important factor B (for best) and least important factor W (for worst) were determined.
3. The preference of the most important factor over all the other factors was evaluated (by using a number that ranges from 1 (equal importance) to 9 (B is extremely more preferred to the other criterion)). This results in the 'Best-to-Others' vector $(a_{B1}, a_{B2}, \dots, a_{Bn})$.
4. The preference of all the factors over the least important factor was established. This is again done using a number ranging from 1 (equal importance) to 9 (the criterion is extremely more importance compared to W). This results in the 'Others-to-Worst' vector $(a_{1W}, a_{2W}, \dots, a_{nW})$.
5. Optimal weights are determined by solving the linear optimization problem:

$$\min \max_j \{ |w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W| \}$$

s.t.

$$\sum_j w_j = 1, \quad (3)$$

$w_j \geq 0$, for all j .

The model (3) is transferred to the linear programming problem:

$\min \xi^L$

s.t.

$$|w_B - a_{Bj}w_j| \leq \xi^L, \text{ for all } j$$

$$|w_j - a_{jW}w_W| \leq \xi^L, \text{ for all } j$$

$$\sum_j w_j = 1 \quad (4)$$

$w_j \geq 0$, for all j

This results in the optimal weights and objective function value (consistency indicator) which has to be as close to zero as possible to attain high consistency.

4. Results

4.1. Overview of results

The results of Study 1 are reported in Table 2. The column Literature lists how many times the factor was mentioned in the literature. A cross in the 'Expert' column indicates that the expert identified the factor as relevant, while a cross in the 'Relevant' column indicates that the factor was mentioned by the expert or in the literature. All factors mentioned in van de Kaa et al. were found to be relevant in at least one of the phases of the dominance process. However, it can be observed that the literature (sources available upon request) primarily focuses on factors in the phase of the decisive battle whereas the expert considers these factors to be relevant during most other phases as well. The factors are explained in van de Kaa and de Vries [41].

The second study resulted in BWM results for three experts. The BWM was used to determine the weights of each factor in the different phases of the dominance process. Table 3 shows the weights resulting from the BWM. Weights for categories and factors are shown for each phase of the dominance process. In Table 4 the global weights are shown. Complete data are available upon request (attached as Appendix 1).

To evaluate if each expert's answers are consistent this method uses the input-based consistency ratio. In Table 4, for each expert and each comparison, that ratio is reported together with its associated threshold value. The consistency ratios are mostly below their associated threshold value which signals a high consistency.

4.2. Interpretation of results

In this section, we will discuss the relevant factors in each stage of the dominance process. The focus will lie on the most important factors (in *italics*) for standard dominance in each stage.

One of the most important factors during the R&D build up phase appears to be *learning orientation*. Indeed, the eventual dominant design is based upon knowledge that is accumulated through R&D during this phase. Complementary assets such as *financial resources* are needed to cover the cost of R&D which is the reason for its importance. The R&D during this stage aims at getting *technological superiority* for the design so it makes sense that the experts valued these three factors as one of the most important ones. If a company cannot do it alone, it is important to form an alliance with other companies with complementary expertise and strength, thereby increasing the *diversity of the network* of actors that support the standard and the *other suppliers* offering, e.g., complementary goods. Another reason to form alliances is to prevent others from forming a competing alliance that is stronger. In such a strong alliance, it should be possible to arrive at a working prototype.

In the second stage, experts found learning orientation to be one of the important factors. Learning is relevant as design improvements are based on knowledge. This knowledge can be gained from within the company or consortium and from outside. Also, it refers to learning by doing and learning from feedback on the prototype. Technological characteristics are also relevant in this second stage, and experts rated flexibility by far as the most important factor. Based on the first experiences internally and the first reactions in the market, companies may aim at further improvements and, if needed, re-positioning. User feedback may be a reason to change initial decisions in positioning. It may, therefore, be needed to modify the design based on first experiences, both technical and from users, so it is important to listen to the market, and think about priorities when changing the initial design.

Companies endorsing the standard that has survived until the third stage, have already invested a lot in technology development but might not yet have seen much rewards. Continued *commitment* for the technology (in which the standard is implemented) is required at this stage. Furthermore, as competitors have entered with competing standards, at this stage it is required to heavily invest in building up an *installed base* before competitors can corner the market. This can especially be accomplished by *marketing communications*, e.g., in the form of pre-announcements and *pricing strategy*, e.g. in the form of penetration pricing. However, such strategies can only successfully be executed when sufficient resources are available such as *financial resources*. As expectation counts for a lot in standards-based industries, brand reputation and credibility increase in importance in this stage. This factor signals strength to the market.

In the fourth stage, only a couple of standards are left and competition will become more fierce so that the importance of further building up *current installed base* increases. This can be accomplished through increasing the availability of *complementary goods*, to be connected via an interface that meets the standard. *Pricing strategy* and *marketing communications* remain important in the fourth stage to further increase the installed base. Brand reputation and credibility becomes somewhat less important.

In the fifth stage, the Post-dominance phase, it is more up to the individual companies than the consortium to keep the standard dominant. At this stage, competition might occur with new entrants that may challenge the dominant standard with an alternative one that allows a substantially higher level of product quality. Installed base and the availability of complementary goods are therefore still important to protect the position of the dominant standard against potential challengers. Then, *pricing strategy* is the most important factor and this does not concern the price of the standard itself but of the products that work with it. Only companies that own sufficient *financial resources* can afford to do this because such resources are required to decrease the price of the technology. It persuades laggards to also buy the technology.

Table 2
Results of study 1.

Phase	R&D Build up			Technical feasibility			Creating the market			Decisive battle			Post-dominance		
	Literature	Expert	Relevant	Literature	Expert	Relevant	Literature	Expert	Relevant	Literature	Expert	Relevant	Literature	Expert	Relevant
Characteristics of the format supporter															
1 Financial strength		X	X		X	X	1	X	X	6	X	X		X	X
2 Brand reputation and credibility		X	X	1	X	X	1	X	X	6	X	X			
3 Operational supremacy		X	X	2	X	X	1	X	X	5	X	X			
4 Learning orientation	1	X	X	2	X	X	1	X	X	6	X	X		X	X
Characteristics of the format															
5 Technological superiority	1	X	X	2	X	X	3	X	X	10	X	X	2	X	X
6 Compatibility	1	X	X	1	X	X	1	X	X	9	X	X		X	X
7 Complementary goods		X	X	1	X	X	1	X	X	7	X	X		X	X
8 Flexibility		X	X	2	X	X	1	X	X	7	X	X		X	X
Format support strategy															
9 Pricing strategy	1	X	X	1	X	X	2	X	X	8	X	X	1	X	X
10 Appropriability strategy		X	X	1	X	X	1	X	X	4	X	X		X	X
11 Timing of entry		X	X	2	X	X	2		X	7		X			
12 Marketing communications		X	X	2	X	X	1	X	X	6	X	X		X	X
13 Pre-emption of scarce assets		X	X		X	X	1	X	X	5	X	X			
14 Distribution strategy					X	X	1	X	X	4	X	X		X	X
15 Commitment		X	X	2	X	X	1	X	X	6	X	X			
Other stakeholders															
16 Current installed base							2	X	X	7	X	X		X	X
17 Previous installed base		X	X				1	X	X	4	X	X		X	X
18 Big fish		X	X		X	X	1	X	X	3		X			
19 Regulator		X	X	2	X	X	1	X	X	6	X	X			
20 Judiciary	1		X	1		X		X	X		X	X			
21 Suppliers		X	X	2	X	X	1	X	X	4	X	X		X	X
22 Effectiveness of the standard development process		X	X	1	X	X				4		X			
23 Diversity of the network	1	X	X	2	X	X		X	X	8	X	X	1	X	X

Table 3

Global weights of factors for standard dominance during each stage of the TLC.

Phase		R&D Build up	Technical feasibility	Creating the market	Decisive battle	Post-dominance
Characteristics of the format supporter						
1	Financial strength	0.10	0.06	0.06	0.03	0.10
2	Brand reputation and credibility	0.03	0.01	0.08	0.06	
3	Operational supremacy	0.03	0.04	0.06	0.04	
4	Learning orientation	0.13	0.10	0.02	0.02	0.06
Characteristics of the format						
5	Technological superiority	0.13	0.07	0.02	0.03	0.04
6	Compatibility	0.04	0.07	0.03	0.03	0.06
7	Complementary goods	0.04	0.09	0.06	0.09	0.08
8	Flexibility	0.08	0.16	0.03	0.02	0.07
Format support strategy						
9	Pricing strategy	0.03	0.01	0.07	0.07	0.18
10	Appropriability strategy	0.02	0.03	0.04	0.03	0.05
11	Timing of entry	0.02	0.03	0.04	0.01	
12	Marketing communications	0.03	0.02	0.08	0.09	0.10
13	Pre-emption of scarce assets	0.03	0.02	0.03	0.03	
14	Distribution strategy		0.02	0.04	0.03	0.08
15	Commitment	0.04	0.04	0.07	0.03	
Other stakeholders						
16	Current installed base			0.07	0.13	0.07
17	Previous installed base	0.04		0.05	0.05	0.01
18	Big fish	0.03	0.05	0.05	0.05	
19	Regulator	0.02	0.02	0.03	0.03	
20	Judiciary	0.01	0.04	0.01	0.02	
21	Suppliers	0.06	0.04	0.04	0.04	0.06
22	Effectiveness of the standard development process	0.03	0.05		0.03	
23	Diversity of the network	0.06	0.03	0.03	0.05	0.03

Table 4
Consistency ratio result.

Phase		R&D Build up			Technical feasibility			Creating the market			Decisive battle			Post-dominance		
		Expert 1	Expert 2	Expert 3	Expert 1	Expert 2	Expert 3	Expert 1	Expert 2	Expert 3	Expert 1	Expert 2	Expert 3	Expert 1	Expert 2	Expert 3
Categories	Input-Based CR	0,17	0,13	0,20	0,20	0,20	0,35	0,20	0,17	0,19	0,20	0,15	0,50	0,19	0,10	0,33
	Associated	0,27	0,27	0,20	0,20	0,20	0,20	0,20	0,15	0,25	0,20	0,20	0,17	0,25	0,27	0,20
	Threshold															
Characteristics of the format supporter	Input-Based CR	0,22	0,15	0,20	0,19	0,17	0,35	0,17	0,19	0,20	0,21	0,19	0,33	0,00	0,00	0,00
	Associated	0,27	0,27	0,20	0,25	0,27	0,20	0,15	0,25	0,20	0,25	0,25	0,20			
	Threshold															
Characteristics of the format	Input-Based CR	0,20	0,15	0,12	0,00	0,20	0,26	0,20	0,45	0,17	0,20	0,21	0,20	0,20	0,00	0,10
	Associated	0,20	0,27	0,25		0,20	0,25	0,20	0,20	0,17	0,20	0,27	0,20	0,20		0,20
	Threshold															
Format support strategy	Input-Based CR	0,20	0,15	0,21	0,21	0,17	0,21	0,22	0,21	0,30	0,22	0,22	0,31	0,20	0,00	0,35
	Associated	0,25	0,33	0,32	0,31	0,35	0,31	0,35	0,31	0,31	0,35	0,35	0,31	0,20	0,17	0,20
	Threshold															
Other stakeholders	Input-Based CR	0,22	0,15	0,73	0,19	0,21	0,19	0,21	0,17	0,14	0,21	0,21	0,21	0,20	0,17	0,31
	Associated	0,35	0,35	0,34	0,30	0,33	0,30	0,31	0,35	0,34	0,36	0,36	0,36	0,20	0,27	0,25
	Threshold															

5. Discussion and conclusion

This paper relates factors for standard dominance specified by van de Kaa et al. [13] to the different phases of the dominance process as defined by Suarez [12]. We find that experts believe that at the beginning of the technology life cycle, it is important to use financial resources to invest in R&D so that a technologically superior prototype can be developed. At the moment that the first prototype has been introduced, it is important to constantly adapt that prototype and therefore keep it flexible. We conclude that when standards are developed in these first two phases, they should not be too restrictive and, e.g., leave enough room open for adaptations. At the moment that the first product (in which the standard is implemented) is launched all factors for standard dominance are equally important but as the battle progresses the importance of increasing installed base and the supply of complementary goods becomes greater. Once a standard has achieved dominance it is important for companies producing products in which this standard is being used to maintain that dominant position through marketing and pricing of their standard-based products.

5.1. Theoretical contributions and practical implications

This paper shows that most of the factors for standards dominance are relevant during all phases of the dominance process but that their relative importance differs. This is the first study to attach weights to these factors in all dominance stages. We contribute to the literature on standards battles in two ways. First, this is one of the first times that empirical research has been conducted on factors for standard dominance in the different stages of the dominance process (exceptions being [9,33,42]). It appears that most factors mentioned in van de Kaa et al. [13] are not only relevant in the actual market battle but also before and after.

In standards-based markets, the uncertainty that is attached to choosing the 'right' standard can be very high. This study decreases that uncertainty by providing an indication to managers which factors are expected to be important during which phase of the dominance process. By applying our results, companies can evaluate their position with respect to each factor in each phase of the dominance process and they might adjust their strategy by influencing certain factors, enhancing their chances to win the standards battle, or conclude that they have no serious chance of winning, the latter can be an important insight as well.

5.2. Limitations and future research recommendations

The method used makes use of pair-wise comparisons by three experts, familiar with both theory and empirical cases. However, other experts might have complementary experiences and insights. Therefore, ideally, the approach should be replicated with other experts, both from industry and academia. Involving them will not be easy, however, because the number of real experts is very limited, and making the comparisons took each expert several hours, so it is uncertain if other experts will be willing to spend this amount of time. They would need even more time if they also commented on their evaluations, but this would be great because it would provide the story behind their assessments.

From Table 1, it appears that most studies focus on the fourth phase. However, our results also point to the relevance and importance of factors for standard dominance in phases 1, 2, 3, and 5 of the technology dominance process, a topic for future research. A next step could be to re-study existing cases, using the findings of our study or, even better, also using findings from replication studies, would allow not only to better understand those historical cases but also to test our model [43]. Finally, although most researchers focused on one specific stage in the technology dominance process some papers focused on multiple stages. For example, a paper written by Amankwah-Amoah [44] on standards for the mobile data storage (floppy disks) discusses the importance of

technological superiority during the 3rd, 4th and 5th phases during the demise of the standard. The most relevant paper was Den Uijl and de Vries who have studied the battle between Blu-ray and HD-DVD and address all subsequent phases of the technology dominance process. De Uijl [31] also studied the case of MP3 (compressed audio files) and the battle between SA-CD and DVD-Audio (high-definition audio platforms). In a more or less similar way, other scholars studied the competition between enterprise reference architectures [32,33]. Our paper contributes to these studies by adding weights of factors for design dominance in each of the five stages. Future research is encouraged to study more longitudinal cases of standards battles focusing on multiple stages of the technology dominance process.

Another question is to which extent these factors and their weights are case-specific and develop during the years. Case descriptions suggest that indeed, factors differ per case, and it is plausible that this applies to weights as well. But they do not differ at random. Patterns do apply and the weights we found reflect these patterns. Some of these patterns may change over time. On the one hand, our approach can be used to investigate old standards battles like the ones between direct and alternating current or between different railway gauges. Next, standards battles were often related to 'duo products' in consumer electronics (a core product related to a complementary product, like a cassette desk and an audio cassette). Meanwhile, the digital revolution has lead to complex systems for which standards are indispensable and for which standards battles will continue to occur. Another move, from linear economy to circular economy, further enhances the need for standards for interfaces between elements of the system. Here 'Design for X approaches' apply: a current design that prepares for the future, e.g., Design for Maintenance, Design for Disassembly and Reassembly, Design for Remanufacturing or Design for Adaptability [45]. Such approaches relate to the 'Rs' in circular economy (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover), and to the main concepts in Product Variety Management: Component commonality, Modularization and Platforms. These concepts rely on stable interfaces between parts of the system, thanks to standards. The circularity extends the variety of relevant stakeholders and the time period during which these standards preferably remain unchanged (while innovation can continue for the interconnected system parts). Future research could follow a similar approach as the one applied in this paper for different cases in different time frames and compare the results, investigating whether weights differ during the years and in these different increasingly complex contexts. First candidates would be technologies with different 'generations', such as game consoles [46,47]. For complex systems, 'smart' systems are candidates. Examples include smart homes, smart industry and smart cities. Related to circular economy, this topic is notably missing in the current standardization roadmaps [48]. Machine-learning provides interesting opportunities for forecasting the outcome of standards battles; Dai, Qualls and Zhu do a first attempt [49].

CRedit authorship contribution statement

Geerten van de Kaa: Investigation, Writing – review & editing, Methodology, Validation, Writing – original draft, Visualization, Conceptualization. **Henk J. de Vries:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors of the research paper: "Success factors for standards during the technology life cycle" states that there are no conflicts of interest that have affected the outcomes of this study, or might have biased our work.

Appendix 1. Complete data; available upon request

Phase		R&D Build up					Technical feasibility					Creating the market					Decisive battle					Post-dominance				
		Expert 1	Expert 2	Expert 3	Local average weight	Global average weight	Expert 1	Expert 2	Expert 3	Local average weight	Global average weight	Expert 1	Expert 2	Expert 3	Local average weight	Global average weight	Expert 1	Expert 2	Expert 3	Local average weight	Global average weight	Expert 1	Expert 2	Expert 3	Local average weight	Global average weight
Characteristics of the format supporter		0,25	0,12	0,49	0,29		0,22	0,22	0,21	0,22		0,18	0,24	0,21	0,21		0,08	0,25	0,12	0,15		0,14	0,26	0,08	0,16	
1,00	Financial strength	0,16	0,30	0,55	0,34	0,10	0,14	0,48	0,22	0,28	0,06	0,24	0,28	0,28	0,27	0,06	0,07	0,23	0,30	0,20	0,03	0,17	0,90	0,75	0,61	0,10
2,00	Brand reputation and credibility	0,06	0,05	0,16	0,09	0,03	0,08	0,04	0,08	0,07	0,01	0,24	0,48	0,47	0,40	0,08	0,14	0,57	0,49	0,40	0,06					
3,00	Operational supremacy	0,09	0,15	0,08	0,11	0,03	0,14	0,19	0,16	0,17	0,04	0,43	0,19	0,18	0,27	0,06	0,61	0,14	0,15	0,30	0,04					
4,00	Learning orientation	0,68	0,51	0,21	0,47	0,13	0,63	0,29	0,54	0,49	0,10	0,10	0,06	0,07	0,07	0,02	0,18	0,07	0,06	0,10	0,02	0,83	0,10	0,25	0,39	0,06
Characteristics of the format		0,62	0,06	0,19	0,29		0,57	0,08	0,51	0,38		0,27	0,10	0,06	0,14		0,27	0,08	0,17	0,17		0,57	0,04	0,15	0,25	
5,00	Technological superiority	0,54	0,30	0,53	0,46	0,13	0,20	0,08	0,29	0,19	0,07	0,18	0,07	0,13	0,12	0,02	0,20	0,15	0,18	0,18	0,03	0,09	0,25	0,18	0,17	0,04
6,00	Compatibility	0,21	0,05	0,20	0,15	0,04	0,20	0,16	0,19	0,18	0,07	0,27	0,15	0,23	0,22	0,03	0,20	0,30	0,08	0,19	0,03	0,20	0,25	0,26	0,24	0,06
7,00	Complementary goods	0,15	0,15	0,07	0,12	0,04	0,40	0,21	0,05	0,22	0,09	0,47	0,47	0,42	0,45	0,06	0,52	0,50	0,47	0,50	0,09	0,20	0,25	0,49	0,31	0,08
8,00	Flexibility	0,09	0,51	0,20	0,27	0,08	0,20	0,55	0,47	0,41	0,16	0,08	0,31	0,23	0,21	0,03	0,09	0,04	0,27	0,13	0,02	0,52	0,25	0,07	0,28	0,07
Format support strategy		0,05	0,23	0,24	0,17		0,13	0,13	0,21	0,16		0,47	0,43	0,21	0,37		0,18	0,43	0,26	0,29		0,23	0,44	0,60	0,42	
9,00	Pricing strategy	0,37	0,16	0,04	0,19	0,03	0,08	0,02	0,05	0,05	0,01	0,21	0,30	0,05	0,19	0,07	0,15	0,23	0,35	0,24	0,07	0,47	0,30	0,54	0,44	0,18
10,00	Appropriability strategy	0,21	0,03	0,13	0,12	0,02	0,14	0,27	0,12	0,18	0,03	0,08	0,09	0,14	0,10	0,04	0,11	0,06	0,08	0,09	0,03	0,18	0,10	0,08	0,12	0,05
11,00	Timing of entry	0,11	0,08	0,18	0,12	0,02	0,35	0,11	0,12	0,19	0,03	0,03	0,18	0,10	0,10	0,04	0,03	0,06	0,04	0,04	0,01					
12,00	Marketing communications	0,11	0,28	0,08	0,15	0,03	0,14	0,11	0,08	0,11	0,02	0,34	0,18	0,14	0,22	0,08	0,36	0,38	0,21	0,32	0,09	0,27	0,30	0,16	0,24	0,10
13,00	Pre-emption of scarce assets	0,06	0,28	0,13	0,16	0,03	0,14	0,16	0,12	0,14	0,02	0,14	0,04	0,08	0,09	0,03	0,15	0,03	0,08	0,09	0,03					
14,00	Distribution strategy						0,04	0,16	0,10	0,10	0,02	0,14	0,09	0,14	0,12	0,04	0,11	0,09	0,14	0,11	0,03	0,08	0,30	0,22	0,20	0,08
15,00	Commitment	0,14	0,16	0,44	0,25	0,04	0,10	0,16	0,41	0,23	0,04	0,07	0,12	0,35	0,18	0,07	0,09	0,15	0,08	0,11	0,03					
Other stakeholders		0,08	0,60	0,08	0,25		0,08	0,57	0,08	0,24		0,08	0,24	0,52	0,28		0,47	0,25	0,44	0,39		0,07	0,26	0,18	0,17	
16,00	Current installed base											0,35	0,03	0,35	0,24	0,07	0,33	0,31	0,34	0,33	0,13	0,52	0,09	0,58	0,40	0,07
17,00	Previous installed base	0,37	0,08	0,07	0,17	0,04						0,14	0,31	0,08	0,17	0,05	0,20	0,09	0,07	0,12	0,05	0,09	0,05	0,06	0,07	0,01
18,00	Big fish	0,15	0,03	0,17	0,12	0,03	0,09	0,11	0,40	0,20	0,05	0,14	0,18	0,19	0,17	0,05	0,06	0,19	0,13	0,13	0,05					
19,00	Regulator	0,06	0,07	0,13	0,09	0,02	0,16	0,06	0,08	0,10	0,02	0,10	0,18	0,05	0,11	0,03	0,07	0,09	0,06	0,07	0,03					
20,00	Judiciary	0,03	0,05	0,07	0,05	0,01	0,39	0,03	0,05	0,16	0,04	0,04	0,05	0,04	0,04	0,01	0,07	0,03	0,03	0,04	0,02					
21,00	Suppliers	0,09	0,21	0,37	0,22	0,06	0,16	0,22	0,16	0,18	0,04	0,14	0,12	0,19	0,15	0,04	0,10	0,12	0,10	0,11	0,04	0,20	0,61	0,18	0,33	0,06
22,00	Effectiveness of the standard development process	0,15	0,21	0,03	0,13	0,03	0,16	0,36	0,16	0,22	0,05							0,03	0,05	0,13	0,07	0,03				
23,00	Diversity of the network	0,15	0,35	0,17	0,22	0,06	0,05	0,22	0,16	0,14	0,03	0,08	0,12	0,10	0,10	0,03	0,14	0,12	0,13	0,13	0,05	0,20	0,25	0,18	0,21	0,03

Data availability

Data will be made available on request.

References

- [1] J. Farrell, G. Saloner, Standardization, compatibility, and innovation, *Rand. J. Econ.* 16 (1) (1985) 70–83.
- [2] M.L. Katz, C. Shapiro, Network externalities, competition, and compatibility, *Am. Econ. Rev.* 75 (3) (1985) 424–440.
- [3] C. Shapiro, H.R. Varian, *Information Rules, a Strategic Guide to the Network Economy*, Harvard Business School Press, Boston, Massachusetts, 1998.
- [4] C. Shapiro, H.R. Varian, The art of standards wars, *Calif. Manage. Rev.* 41 (2) (1999) 8–32.
- [5] S.R. Gallagher, The battle of the blue laser DVDs: the significance of corporate strategy in standards battles, *Technovation* 32 (2) (2012) 90–98.
- [6] S.R. Gallagher, S.H. Park, Innovation and competition in standard-based industries: a historical analysis of the U.S. home video game market, *IEEE Trans. Eng. Manage.* 49 (1) (2002) 67–82.
- [7] M.A. Cusumano, Y. Mylonadis, R.S. Rosenbloom, Strategic maneuvering and mass-market dynamics: the triumph of VHS over Beta, *Bus. Hist. Rev.* 66 (1) (1992) 51–94.
- [8] R.S. Rosenbloom, M.A. Cusumano, Technological pioneering and competitive advantage: the birth of the VCR industry, *Calif. Manage. Rev.* 29 (4) (1987) 51–76.
- [9] S. Den Uijl, H.J. de Vries, Pushing technological progress by strategic manoeuvring: the triumph of Blu-ray over HD-DVD, *Bus. Hist.* 55 (8) (2013) 1361–1384.
- [10] M.A. Schilling, Technological lockout: an integrative model of the economic and strategic factors driving technology success and failure, *Acad. Manage. Rev.* 23 (2) (1998) 267–284.
- [11] M.A. Schilling, Technology success and failure in winner-take-all markets: the impact of learning orientation, timing, and network externalities, *Acad. Manage. J.* 45 (2) (2002) 387–398.
- [12] F.F. Suarez, Battles for technological dominance: an integrative framework, *Res. Policy* 33 (2) (2004) 271–286.
- [13] G. van de Kaa, J. van den Ende, H.J. de Vries, E. van Heck, Factors for winning interface format battles: a review and synthesis of the literature, *Technol. Forecast. Soc. Change* 78 (8) (2011) 1397–1411.
- [14] J. Rezaei, Best-worst multi-criteria decision-making method, *Omega* 53 (2015) 49–57.
- [15] J. Rezaei, Best-worst multi-criteria decision-making method: some properties and a linear model, *Omega* 64 (2016) 126–130.
- [16] W.J. Abernathy, J.M. Utterback, Patterns of industrial innovation, *Technol. Rev.* 80 (7) (1978) 40–47.
- [17] J.M. Utterback, *Mastering the Dynamics of Innovation*, Harvard Business School Press, Boston, 1994.
- [18] P. Anderson, M.L. Tushman, Technological discontinuities and dominant designs: a cyclical model of technological change, *Adm. Sci. Q.* 35 (4) (1990) 604–633.
- [19] M.L. Tushman, L. Rosenkopf, Organizational Determinants of technological change: toward a sociology of technological evolution, *Res. Organ. Behav.* 13 (1992) 311–347.
- [20] H. Liu, Dynamics of pricing in the video game console market: skimming or penetration? *J. Mark. Res.* 47 (3) (2010) 428–443.
- [21] J.L. Funk, Standards, dominant designs and preferential acquisition of complementary assets through slight information advantages, *Res. Policy* 32 (8) (2003) 1325–1341.
- [22] C.W.L. Hill, Establishing a standard: competitive strategy and technological standards in winner-take-all industries, *Acad. Manag. Exec.* 11 (2) (1997) 7–25.
- [23] M.A. Schilling, *Strategic Management of Technological Innovation*, McGraw-Hill, New York, USA, 2020.
- [24] R. Garud, A. Kumaraswamy, Changing competitive dynamics in network industries: an exploration of sun microsystems' open systems strategy, *Strat. Manage. J.* 14 (5) (1993) 351–369.
- [25] J. West, How open is open enough? Melding proprietary and open source platform strategies, *Res. Policy* 32 (2003) 1259–1285.
- [26] P.M. Wiegmann, H.J. de Vries, K. Blind, Multi-mode standardisation: a critical review and a research agenda, *Res. Policy* 46 (8) (2017) 1370–1386.
- [27] K.J. Boudreau, L.B. Jeppesen, M. Miric, Competing on freemium: digital competition with network effects, *Strat. Manage. J.* 43 (7) (2022) 1374–1401.
- [28] X. Ferras-Hernandez, P.A. Nylund, A. Brem, The emergence of dominant designs in artificial intelligence, *Calif. Manage. Rev.* (2023) 1–19.
- [29] J. Lee, D.E. O'Neal, M.W. Pruett, H. Thoams, Planning for dominance: a strategic perspective on the emergence of a dominant design, *R&D Manag.* 25 (1) (1995) 3–15.
- [30] J.L. Funk, The product life cycle theory and product line management: the case of mobile phones, *IEEE Trans. Eng. Manage.* 51 (2) (2004) 142–152.
- [31] S. Den Uijl, The Emergence of De-facto Standards, Erasmus Research Institute of Management, Rotterdam, 2015 repub.eur.nl/pub/77382/ EPS2014328LIS9789058923813.pdf.
- [32] E. Rogante, H.J. de Vries, R. van Wessel, Factors that influence the dominance of an enterprise reference architecture: a comparative case study. Appendix 1: description of the factors favouring the emergence of single or multiple designs, *J. Stand.* 1 (1) (2022).
- [33] E. Rogante, R. van Wessel, H. de Vries, Factors that influence the dominance of an enterprise reference architecture: a comparative case study, *J. Stand.* 1 (2022).
- [34] X.Q. Wang, S. Zander, Extending the model of internet standards adoption: a cross-country comparison of IPv6 adoption, *Inf. Manage.* 55 (4) (2018) 450–460.
- [35] A. Hovav, R. Patnayakuni, D. Schuff, A model of internet standards adoption: the case of IPv6, *Inf. Syst. J.* 14 (3) (2004) 265–295.
- [36] F. Wijnen, Means versus ends in opaque institutional fields: trading off compliance and achievement in sustainability standard adoption, *Acad. Manage. Rev.* 39 (3) (2014) 302–323.
- [37] S. Bakker, H. van Lente, M. Meeus, Dominance in the prototyping phase—the case of hydrogen passenger cars, *Res. Policy* 41 (2012) 871–883.
- [38] G. van de Kaa, M. van Ek, L.M. Kamp, J. Rezaei, Standards contests for wind turbine technologies: the battle between gearbox and direct drive, *Technol. Forecast. Soc. Change* (2020).
- [39] J. Rezaei, O. Kothadiya, L. Tavasszy, M. Kroesen, Quality assessment of airline baggage handling systems using SERVQUAL and BWM, *Tour. Manage.* 66 (2018) 85–93.
- [40] G. Yadav, S.K. Mangla, S. Luthra, S. Jakhari, Hybrid BWM-ELECTRE-based decision framework for effective offshore outsourcing adoption: a case study, *Int. J. Prod. Res.* (2018) 1–20.
- [41] G. van de Kaa, H. de Vries, Factors for winning format battles: a comparative case study, *Technol. Forecast. Soc. Change* 91 (2) (2015) 222–235.
- [42] H.J. de Vries, Blu-ray vs. HD-DVD: how to win a battle between competing standards? in: H. Lee, H. Zoo, D. Choi (Eds.), *The 4th Industrial Revolution and Standardization: Case Collection* Parkyoung Publishing Company, Seoul, 2019, pp. 61–81.
- [43] J. Dul, T. Hak, *Case Study Methodology in Business Research*, Oxford, UK, Butterworth-Heinemann, 2008.
- [44] J. Amankwah-Amoah, Competing technologies, competing forces: the rise and fall of the floppy disk, 1971–2010, *Technol. Forecast. Soc. Change* 107 (2016) 121–129.
- [45] C. Sassanelli, A. Urbinati, P. Rosa, D. Chiaroni, S. Terzi, Addressing circular economy through design for X approaches: a systematic literature review, *Comput. Ind.* 120 (2020) 1–23.
- [46] J. Kramer, H.J. de Vries, Impact of backwards compatibility on standards dominance – the case of game consoles, in: 14th Annual Standardisation Conference 'Standardisation and Corporate Intelligence', Aachen, 2009.
- [47] T. Kretschmer, J. Claussen, Generational transitions in platform markets—the role of backward compatibility, *Strat. Sci.* 1 (2) (2016) 90–104.
- [48] D.K.E. DIN, *Standardization Roadmap Circular Economy*, VDI, Berlin, DIN, 2023.
- [49] H. Dai, W.J. Qualls, Y. Zhu, Win, lose, or draw? Forecasting the outcome of a race toward a dominant formal standard with machine learning, *Technol. Forecast. Soc. Change* 205 (2024) 123499.