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DOI
10.1016/j.jengtecman.2022.101693

Publication date
2022

Document Version
Final published version

Published in
Journal of Engineering and Technology Management - JET-M

Journal of Engineering and Technology Management 65 (2022) 101693

Contents lists available at ScienceDirect

Journal of Engineering and Technology Management

journal homepage: www.elsevier.com/locate/jengtecman

Battles in space: De-facto standardization of Global Navigation Satellite Systems

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ARTICLE INFO

Keywords:
GNSS
Standards battle
Technology battle
De facto standard
Standard dominance

ABSTRACT

As the European Union announced the final rollout of the second-generation satellite for their Galileo Global Navigation Satellite System by 2021, stakeholders from comparable systems contemplate the potentially disrupting effects such rollout could cause. This paper explores the battle for standards that facilitate Global Navigation Satellite Systems, with the focus on GPS, GLONASS, and Galileo. The paper shows that although GPS is still in the lead, Galileo is closing in. It appears that GLONASS is trailing behind. Four factors for standard dominance were most important: brand reputation and credibility, operational supremacy, technological superiority, and compatibility.

1. Introduction

Survey and navigation technology has been integrated into consumers' daily lives over the last two decades. The use of Global Navigation Satellite Systems (GNSS) has proven to be an essential innovation for several industries such as farming, financial services, and telecommunications, providing tracking, surveying, and timing services. GNSS are to be considered as industry standards, because they provide technical specifications for these aforementioned implementations (David and Greenstein, 1990) and provide a solution to matching problems (De Vries, 1997) between governments, space agencies and chip manufacturers. As of now, two dominant standards for GNSS are available; Global Positioning System (GPS) and Global'naya Navigazionnaya Sputnikovaya Sistema (GLONASS) (Cojocaru et al., 2009). As the worldwide location and timing services available through GNSS services have become significantly more important over the years, experts have advised creating a robust alternative to mitigate the economic impact if anything happens to these systems (Narins et al., 2012). GNSS play a key role in shaping the technological competition between world powers, by providing greater security and efficiency in all types of transports and an overall improvement in the quality of life (Radojevic, 2020). Galileo's second-generation satellites are currently under development. While GPS and GLONASS are two different systems, it is common practice to simultaneously use both systems in multi-GNSS positioning (Przestrzelski et al., 2017). The existence of multi-GNSS positioning and the global fragmentation of the GNSS market allow the presence of more than one dominant standard (or dominant design) (De Vries Henk et al., 2011), namely GPS and GLONASS. Consequently, the addition of a third independent GNSS standard could destabilize the current status quo and start a technology battle for standard dominance. To pursue this analysis, the two dominant GNSS (GPS and GLONASS) have been selected for the comparison to a novel market entrant, that is Galileo.

Such a battle for standards is not new. Throughout history, many cases of standards battles have been discussed in the literature by scholars interested in de-facto standardization (Gallagher and Park, 2002; Shapiro and Varian, 1999). The battle between Betamax and

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https://doi.org/10.1016/j.jengtecman.2022.101693
Received 10 June 2021; Received in revised form 17 February 2022; Accepted 13 June 2022
Available online 4 July 2022
0923-4748/

VHS is still etched in the memory of these scholars (Cusumano et al., 1992). A recent example was the battle between Sony's Blu-ray and Toshiba's HD-DVD (Gallagher, 2012). In that battle, Sony won by, amongst others, providing complementary products and utilizing its technology as a component in ancillary products (Gallaghar, 2012). Factors for standard success have been distilled from these battles (Schilling, 1998; Suarez, 2004; Van de Kaa et al., 2011). However, the battles are mostly found in the consumer electronics (Schilling, 2003) and ICT sectors (Jakobs, 2013; Oshri and De Vries, 2008).

This paper studies the battle between Global Navigation Satellite Systems standards and raises the question of which factors affect standard dominance in that context (according to experts). More specifically, it attempts to assign weights to standard dominance factors and determine which standard will have the highest chance of achieving dominance. This will be done by interviewing twelve experts and utilizing the best-worst method (Rezaei, 2015).

We contribute to the literature on de-facto standardization (Gallagher and Park, 2002; Shapiro and Varian, 1999) by analysing a standards battle that has not been studied before. We also contribute to the literature by assigning weights to factors for standard dominance and providing additional empirical evidence that the outcome of these battles can be explained, also in this new context. The empirical context is novel in that it consists of two existing standards where a new standard is introduced. The novel technology is not expected to provide an overall higher proposed technological value to its customers, and the question is whether it can battle with both systems' dominant positions.

2. The GNSS market and applications

GNSS is used for satellite navigation. Positioning is established by triangulation; the distance between the satellites and GNSS receivers is measured "using the speed of light and the time taken for the GNSS signal to travel from each satellite to the receiver" (Zito et al., 1995), furthermore, the phase observations derived from the phase comparison method between the satellite and GNSS receivers are used in precise GNSS measuring techniques. A receiver needs to be in contact with at least four satellites to calculate its position. Three satellites will determine the latitude, longitude, and height, while the fourth satellite is required to synchronize the receivers' internal clock. These satellites send data to receivers to process the information and calculate the users' live location up to five meters precisely (Li et al., 2015). When the receiver is connected to more than four satellites, the positioning's accuracy will increase significantly (Rash, 2019). Accuracy further increases when multiple GNSS constellations are combined (Pan et al., 2019). Moreover, to accurately determine the receiver coordinates or other parameters relevant to GNSS, knowledge is required of the following factors: knowledge of the GNSS satellites' positions at the time of the signal transmission, clock offset, atmospheric propagation delays, uncertainty for the carrier-phase observations, and smaller offsets caused by instrumental delays (Teunissen and Montenbruck, 2017). On top of that, post-processing can be applied to increase the supplied data's accuracy even more (Bahadur and Nohutcu, 2019).

GNSS is a complex market when it comes to assessing its economic outlook. Satellite systems are implanted in products ranging from $2 chips to $300.000 navigation installations for military submarines (Kaplan and Hegarty, 2017). Measuring its market value and growth rate gets even harder when considering the set of value-added services deriving from all sorts of devices making use of GNSS. The European GNSS Agency (GSA) assessed a global installed base of 6.4 billion devices and a global revenue stream of $150 billion in 2019, with the Asia-Pacific segment accounting for over 50 % of the global installed base and 30 % of the global revenues. The same Agency estimates a 50 % growth of the number of devices and a 100 % growth of the revenues in the next 10 years, meaning that the average price of value-added services associated with GNSS will increase (GSA, 2019).

The applications of GNSS can be found both at a consumer and enterprise level. The consumer market is driven by system integrators, in charge of assembling the chips (or receivers) with other components of the devices. The majority of these devices pertains to either smartphones or wearables. Conversely, enterprise applications mostly consist of aviation, maritime navigation, agriculture, drones, geomatics, search and rescue, driver advisory systems, rail, and critical infrastructures (Pereira, 2015). The main sources of global revenues are smartphones and road vehicles, with a notable growth expected for the wearables segment in the next 10 years (GSA, 2019).

The selection of a GNSS system to be used within such a device pertains to the receiver used within the product. It is common to include the capability within a device to include multiple GNSS's signals. The end user occasionally has the possibility to switch between GNSS within their device, otherwise, the user must switch device to change GNSS.

GPS, originally Navstar GPS, was in development by the United States military to provide geolocation services for military operations (Zito et al., 1995). It became available to the public in 1983 and is still under the United States military (Hartl and Wlaka, 1996). The GLONASS constellation, operational since 1976, is under the wings of the Russian Federal Space Agency (Harvey, 2007). It was the first fully operational system after GPS. The Galileo GNSS project has been in development since the early 2000s and is planned to be fully operational by 2021 (European Commission, 2020). The system's second generation is still in development by numerous stakeholders, co-funded by the European Space Agency (ESA) and the European Union (European Commission, 2020). Galileo and GPS & GLONASS's key difference is that Galileo is a GNSS fully dedicated to civilian purposes. While GPS, GLONASS, and Galileo slightly differ on a technical level, they also differ in the services they provide. The main differences between the GNSS's included in this study are summarized as follows:

3. Theoretical background

Various scholars have studied the topic of standards battles, albeit from multiple angles. Notably, the literature on the economics of standards started to blossom in the 1980s. These scholars took, for instance, an evolutionary perspective and described how the emergence of technology in a specific market can be the result of a dynamic process rather than of a static one (Arthur, 1989) and how such a dynamic process shows path dependencies (Arthur, 1989), which could potentially lead to the dominance of a less functional (or obsolete) technology (Liebowitz and Margolis, 1995). In these years, theories related to hierarchies and "trajectories" within the dominance process (Dosi, 1982) started spreading. These trajectories would result in dominant designs that define complete product categories (Utterback and Suarez, 1993).

Around the same time, network economists emphasized aspects based on the network's characteristics lying behind the technology, such as its size or its actors' bargaining power (Katz and Shapiro, 1985; Ehrhardt, 2004) as factors for standard dominance. They pointed to factors like previous and current installed base and network externalities. Network externalities refer to the phenomenon whereby technology increases in value as more users adopt it (which applies to, e.g., mobile phones and fax machines). Within this stream, scholars also demonstrated strong linkages with the microeconomics theory of complementary goods (Farrell and Saloner, 1985; Katz and Shapiro, 1985). They emphasized the degree of compatibility and the availability of complementary goods as factors for dominance.

Furthermore, some scholars have approached the phenomenon from the lens of institutional entrepreneurship (Scott, 1994). This includes the actions as done by actors to accomplish projects within an institutional setting. They emphasize the importance of forming organizational communities to support technological designs (Wade, 1995), as well as the country's governmental tendency to innovate and standardize (Zhan and Tan, 2010). Thus, these scholars identify socio-political processes as determinants of standard dominance (Tushman and Rosenkopf, 1992).

In a situation where two or more technologies are competing in a market, scholars have concluded that the outcome is based not only on their technological superiority but also on various other factors (Suarez, 2004). Different scholars have explored the concept of standard dominance and how it is achieved within specific markets. Scholars in technology management explored how standards and dominant designs are established using firms' strategic behavior in markets characterized by the network effects (Shapiro and Varian, 1999). They have studied various standards battles between two major companies (Cusumano et al., 1992; Gallagher, 2012). These battles commonly result in pure monopolies in that the winner takes it all (Hill, 1997). However, the result can also be a stalemate where a duopoly is formed (Gallagher and Park, 2002). Even the option of harmonious cooperation with the incumbent and novel technology is an option, as illustrated in the UK fiber-optics industry. It was shown that through formal and informal cooperation, the novel fiber-optics-based technology could coexist with the incumbent copper-based technology (Spedale, 2003).

Starting in the 1990s, scholars (Suarez, 2004; Schilling, 1998, 2002; Van de Kaa et al., 2011, 2020) further investigated additional factors that affect standard dominance. For example, they state that standards can achieve dominance dependent upon their promoting organization's position in the network of companies active in the industry (Van de Kaa, 2018). Researchers have also emphasized the relevance of timing of entry strategies and their impact on firms' survival (Suarez and Utterback, 1995; Yamanda and Kurokawa, 2005). Scholars also explored which technological attributes resulted in the technological superiority of a product over its competitors. Van de Kaa et al. (2011) have performed an extensive literature study covering multiple streams of literature and derived 29 factors for standard dominance. To date, this is the framework for standard dominance that is most complete, and it will thus be applied in this paper. In addition, given the political relevance of the GNSS battle, the factor "geopolitics" was added to such framework.

4. Methodology

Three stages are performed to assign weights to standard dominance factors and determine which standard will have the highest chance of achieving dominance in the specific case under investigation. First, relevant factors for standard dominance are determined by reviewing the literature that reports on the battle and conducting interviews with four experts (see Tables 1 and 2). The interview length during each stage was one hour and interviews were held over Microsoft Teams in the period September to October 2020.

Criteria for the selection of experts are as follows: one must have at least a master's degree in a relevant field and work or academic experience in the field of GNSS.

Table 1
GNSS specifications summarized (Based on (Cojocaru et al., 2009; Department of Defense, 2008; ESA, 2021; GPS.gov, 2021; Li et al., 2015, 2017).

	GPS	GLONASS	Galileo
Owner	United States of America	Russian Federation	European Union
Initial service	Dec 1993	Sept 1993	Dec 2016
Nominal number of satellites	27 + 3 spares	21 + 3 spares	24 + 6 spares
Orbits with respect to the equatorial plane	56°	64.8°	56°
Coding	CDMA	FDMA & CDMA	CDMA
Coordinate system	WGS84	PZ90.02	GTRF
Frequencies	L1 1575.42 MHz L2 1227.60 MHz L5 1176.45 MHz	L1 1602.00 MHz L2 1246.00 MHz L3 1202.025 MHz	E1 1575.42 MHz E5a 1176.45 MHz E5b 1207.14 MHz E6 1278.75 MHz
Services	Standard Positioning Service (SPS) and Precise Positioning Service (PPS)	Standard Positioning Service (SPS) and Precise Positioning Service (PPS)	Open Service (OS), Public Regulated Service (PRS), and Commercial Service (CS)

For further technical details we refer the reader to the GNSS User Technology Report, which provides an in-depth look at the current state of the GNSS technology European GNSS Agency (2019, 2020).

Table 2
First stage interviews.

#	Background	Expertise besides GNSS	Function
1	Academia	Satellite technology, CubeSats, constellations of small satellites, electrical interfaces, bus architecture, operational logic, satellite reliability	Researcher
2	Academia	Theoretical Particle Physics, Particle Physics, Radiation, Cosmology, Detectors, Experimental Particle Physics, Space, High Energy Physics, Radiation Protection, Dosimetry	Assistant professor
3	Academia	Astrodynamics, space missions, positioning of objects flying around earth, precision of locations of satellites	Professor
4	Academia	GIS technology, Location Based services, Geo Information, Environmental Modelling and Planning	Assistant professor

During the first interview stage, questions asked were explorative in nature. Examples of questions include "Which factors played a role in the battle?", "What were, according to you, the success or fail factors of the standard?" and "What was, according to you, the most relevant factor for the outcome of the battle?".

A factor was taken into account when it was either mentioned in the literature or by an expert. When a factor was found in any of the two sources, it was investigated whether it was already mentioned in the list of factors mentioned in Van de Kaa et al. (2011), and if not, it was included as an unknown factor. In the second stage, factors were assigned weights by utilizing the best worst method (BWM). Section 4.1 explains the rationale for using that method and its specifics. Seven experts participated in the BWM study (see Table 3).

During the second stage interviews, the interviews were split up into two parts. The first part addressed questions regarding the background of the expert, such as "Can you tell us a bit about your professional experiences with GNSS?" and "What work did you do at the time that the standards were developed?". The second part of the interviews had the objective of assigning weights to the factors. The type of questions asked were more structured (see Section 4.1).

In the third and final stage, expert 2 was interviewed who reflected on the results. The interviewee works in industry as a GNSS system architect with expertise on Model-Based System Engineering, Down-stream Earth Observation, System Integration and Verification. The decision to choose this expert is rooted in the selection criteria, as the expert scored extremely favourable on these criteria. During this interview, the ranking of each factor and category was assessed by asking questions of relevance and potential causation of the ranking.

4.1. BWM

The Best Worst Method (BWM) (Rezaei, 2015, 2016) was used to arrive at weights. This is a 'multi-criteria decision-making method' that compares criteria in pairs on a scale of 1 to 7. In our study criteria are factors and categories. The BWM was chosen over other methods that compare pairs of criteria such as AHP as the number of criteria to be compared is very high and the BWM method is known for requiring fewer comparisons in that case. Initially, the factor categories are being compared to each other. Then, the factors related to these categories are ranked relative to each other. The BWM consists of the following five steps:

Step 1: Assigning a set of decision criteria $\{c_1, c_2, \ldots., c_n\}$. These criteria are the relevant factors for standard dominance for GNSS systems that came out of the analysis' stage 1.

Step 2: Assigning the best (e.g., the most important) and the worst (e.g., the least important) factor for standard dominance.

Step 3: After the best and worst criteria are defined, the best factor is compared to the other factors on a scale of 1–9, where 1 is of equal importance and 9 is absolutely less important. This results in a best-to-others vector $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$ where A_{Bj} is the preference of the best factor B to factor *j*.

Step 4: Other factors are compared to the worst factor in line with the previously mentioned scale. This results in an others-to-worst vector $A_W = (a_{1W}, a_{2W}, \ldots., a_{nW})^T$ where A_{jW} refers to the preference of the criterion *j* to the worst factor W.

Step 5: Optimal weights are defined for each factor by solving the following problem:

$$\min \xi^L \tag{1}$$

s.t.

Table 3
Characteristics of the experts.

#	Background	Expertise	Function
1	Academia	Space systems, microsats	Associate professor
2	Industry	Model-Based System Engineering, Down-stream Earth Observation, System Integration and Verification	GNSS system architect
3	Academia	Recursive data processing for kinematic GPS surveying, Data quality control, SBAS, Precise Point Positioning	Associate professor
4	Industry	Augmentation of GNSS, Data processing, Land surveying	Operational manager
5	Industry	GNSS infrastructure programmer, GNSS engineering, geodic infrastructure and engineering	GNSS entrepreneur
6	Industry	GNSS system engineer, GNSS interface engineering, GNSS messaging	GNSS system architect
7	Industry	GNSS satellite systems engineer, Spacecraft Controller	GNSS System Engineer

$$\left|w_B - a_{Bj}w_j\right|\left| \leq \xi^L, \quad for \quad all \quad j\right. \tag{2}$$

$$\left|w_j - a_{jw}w_W\right|\left| \leq \xi^L, \quad for \quad all \quad j\right. \tag{3}$$

$$\sum_j w_j = 1 \tag{4}$$

$$w_j \geq 0, \quad for \quad all \quad j \tag{5}$$

When solving this problem, a unique solution; the optimal weights $(w_1{}^*, w_2{}^*, \ldots, w_n{}^*)$ is established. Also, an indicator of consistency is arrived at; ξ^*. The closer this ratio is to zero, the higher the level of consistency of the model.

We have also evaluated each of the standards with respect to each factor. An additive model was used to calculate the overall values of each technology:

$$Value_{Technology \quad i} = \sum_j w_j^* T_{ij} \tag{6}$$

w_j^* shows the optimal weight of criterion *j* and T_{ij} shows the evaluation of technology *i* concerning criterion *j,* which can take on four values. 0 represents a non-relevant factor. If a technology performs weakly on the factor, it is assigned a score of 3. If it performs moderately, it is given a score of 5. If it scores well, it is given a score of 7. These values were assigned based on the insights that were gathered during the regular BWM interviews. The values were validated by expert 2.

5. Results

5.1. Relevant factors

Stage 1 of the study resulted in 30 relevant factors divided into five categories. The factors are briefly explained below; more detailed explanations can be found in Van de Kaa et al. (2011). The first category refers to the characteristic of the format supporter. This refers to the financial resources needed to finance the strategies and tactics used to achieve standard dominance (Schilling, 1999). Also, it refers to brand reputation and credibility as expectations count for a lot in standards-based industries (Shapiro and Varian, 1999). Furthermore, operational supremacy, in the form of, e.g., a superior production capacity, can give stakeholders a competitive advantage (Suarez and Lanzolla, 2005). Finally, a firm's learning orientation can affect standard dominance; if firms can effectively apply the knowledge gained from earlier cases of standardization in which they were involved, this can give them an advantage Klepper and Kenneth (2000).

Standard dominance is also affected by the characteristics of that technology. For example, this refers to technological superiority in terms of, e.g., resolution and accuracy. Furthermore, the extent to which designs can be compatible with competing designs can increase their market uptake (Lee et al., 2003). As one respondent noted: "Ideally, you can switch from one system to the other as end-users." Furthermore, the availability of complementary goods (e.g., videotapes or games) can increase the demand for the core good (video recorder or gaming console) (Hill, 1997; Schilling, 2002). Finally, researchers have shown that when standards are more flexible and can be changed more quickly to changing user requirements, this positively affects their chances of success (Van de Kaa and De Vries, 2015).

Strategies and tactics (format support strategy) can be used to try to increase a standard's installed base. Examples include penetration pricing (pricing below cost) (Katz and Shapiro, 1985) and appropriability strategy (Teece, 1986). The last aspect refers to, e.g., the extent to which the standard is open, which increases the chances that it will be adopted (Khazam and Mowery, 1994). Another strategy includes timing of entry; when the point at which technology enters is early, it can quickly build up an installed base (as was the case for GSM) (Lieberman and Montgomery, 1998). It can also pre-empt scarce assets (Barney, 1991), which are, for the case of GNSS, the field of location in the orbit and bandwidth distribution; as stated by one expert, "*Frequencies are regulated but are a scarce asset and can influence the battle*." Marketing refers to, e.g., preannouncements (Besen and Farrell, 1994) that can increase the standard's expected market share. Furthermore, firms with a better distribution strategy can more effectively distribute the product to the final consumer and, therefore, have an advantage (Wonglimpiyarat, 2005). Finally, more committed firms will have a better chance of achieving success with their standard (Van de Kaa and De Vries, 2015).

The fourth category of factors relates to the stakeholders in the standardization arena that affect standard dominance. First, under the influence of network effects, the number of actors that adopt a standard (or have adopted a previous generation standard) is a factor for standard success (Van de Kaa et al., 2011). In that respect, a big fish (a large party that en masse adopts a standard) can result in standards attaining (instant) dominance (Garud and Kumaraswamy, 1993). A similar situation occurs when a regulator enforces a standard (Axelrod et al., 1995). An example given by experts is that it is forbidden to sell GNSS-related products without GLONASS capabilities within the Russian Federation. This mandate forces producers of GNSS-related systems to implement the GLONASS standard. A judiciary entity can also restrict the use of a standard when, e.g., there are risks of monopolization by a single firm (Mahajan et al., 1993).

Suppliers of material used for the production of technology that incorporates the standard affect its availability and, thus, standard dominance. In the consumer electronics sector, the platform war for ninth-generation gaming consoles started at the end of 2020. Limited production capacity due to hardware shortages due to the covid-19 pandemic has dramatically decreased the availability of both gaming consoles, decreasing their chances of achieving market dominance. Also, the effectiveness of the standard development process in terms of, e.g., its duration may negatively impact that likelihood that a standard is arrived at (Lehr, 1992). Finally, the composition of the network of actors that support a standard affects the chances that the standard is adopted on a large scale; the literature argues and shows that more diverse networks result in a higher installed base for the standard (Van de Kaa and De Vries, 2015).

Geopolitics is a factor that was not mentioned before in the literature, and it refers to the interplay between nation-states through international relations, as influenced by geographical factors. It includes political and ideological functions, which could affect the outcome of a standards battle. As mentioned by experts, the Galileo project was initiated to satisfy Europe's need for GNSS independence. An expert pointed out that "*It is a power game because all the big players in the political world want to have their own navigation system*". When the EU announced that they were developing their GNSS, an expert mentioned that "*the US tried to convince the EU that they did not need a separate GNSS system because the costs would not outweigh the benefits*". This shows the relevance of geopolitics within the field of GNSS.

The fifth category of factors contains market mechanisms, including network effects, the phenomenon whereby technology increases in value the more it is being adopted (Farrell and Saloner, 1986; Katz and Shapiro, 1985), often resulting in bandwagon effects. Furthermore, the number of options available and the rate of technological change can both create uncertainty. Finally, the more people get familiar with technology, the more they become locked into that technology, increasing the switching costs to alternative technologies (Zhou et al., 2006).

5.2. BWM results

This section presents the results of the BWM research. An important step is to calculate the consistency of the answers given in the interviews with the experts. This is done by determining the consistency ratios. In Table 4, the consistency ratios are given; these numbers show good consistency results.

Table 5 shows the final results. The most important factors for potential standard dominance according to the BWM are operational supremacy with a score of 0,10, brand reputation and credibility scoring 0,08, technological superiority scoring 0,08, and compatibility scoring 0,08.

Table 6 presents the final part of the research, the ranking of the three alternative standards. Both GPS and Galileo have a high chance of achieving dominance (their scores are 5.87 and 5.37, respectively). It appears that GLONASS is lagging behind (the final score is 4.28).

6. Discussion

6.1. Interpretation of the results

The most important factor for standard dominance for GNSS systems is operational supremacy (0,10). This factor refers to the (static) resources owned by firms that make them outcome competitors. These may include the production capacity that is needed to develop products in which the standard is incorporated (Suarez and Lanzolla, 2005). Interestingly, although the literature has mentioned that this factor is relevant, actual empirical evidence of the importance of this factor is missing (Van de Kaa and De Vries, 2015). Operational supremacy as a factor was prevalent during most interviews, as one interviewee referred to Galileo as the superior system due to their resource allocation. Another interviewee stated specific perspective on the application of resources. "GNSS systems need to be flexible and AGILE in the future … adapting IT in system engineering efforts, the best [GNSS] will be leading". Apparently, the production capacity needs to be flexible and react to events where possible. When reflecting on the scores in Table 6 regarding operational supremacy GPS and Galileo have similar results. However, as one interviewee stated, this position of GPS might be in peril, as their first-mover advantage is slowly turning into a disadvantage due to the political climate in the United States of America, which might cause Galileo to get ahead.

Experts also indicated that technological superiority is an important factor. That factor is also mentioned in prior literature on standards battles (Wade, 1995). However, it is often stated that the most technologically superior standard does not always win the battle for standard dominance (David, 1985). This also appears to be the case for the battle under investigation in this paper. Experts indicated that GPS has the highest chance of achieving market dominance, while they also indicate that the Galileo standard is technologically superior compared to GPS. An expert comments: "Galileo is technically superior, …, it improved resolution with a

Table 4
Consistency ratio results.

	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Categories	0.07	0.10	0.12	0.09	0.07	0.06	0.11
Characteristics of the format supporter	0.18	0.07	0.10	0.10	0.11	0.06	0.12
Characteristics of the format	0.09	0.09	0.08	0.10	0.12	0.06	0.11
Format support strategy	0.08	0.16	0.09	0.08	0.06	0.08	0.07
Other stakeholders	0.07	0.06	0.05	0.07	0.07	0.08	0.07
Market characteristics	0.09	0.08	0.09	0.11	0.09	0.09	0.08

Table 5
Local and global average weights.

Categories and Factors	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Local average weight	Global average weight
Characteristics of the format supporter	0.23	0.38	0.17	0.49	0.48	0.05	0.09	0.27	
Financial Strength	0.24	0.17	0.05	0.22	0.53	0.18	0.12	0.22	0.06
Brand reputation and credibility	0.18	0.60	0.14	0.16	0.32	0.49	0.24	0.30	0.08
Operational Supremacy	0.53	0.06	0.58	0.55	0.11	0.28	0.59	0.39	0.10
Learning orientation	0.06	0.17	0.23	0.06	0.05	0.05	0.05	0.10	0.03
Characteristics of the format	0.23	0.42	0.39	0.19	0.28	0.15	0.13	0.26	
Technological superiority	0.47	0.32	0.41	0.22	0.14	0.18	0.53	0.32	0.08
Compatibility	0.19	0.55	0.11	0.55	0.23	0.28	0.21	0.30	0.08
Complementary goods	0.05	0.07	0.24	0.06	0.58	0.49	0.05	0.22	0.06
Flexibility	0.28	0.05	0.24	0.16	0.05	0.05	0.21	0.15	0.04
Format support strategy	0.39	0.10	0.26	0.14	0.08	0.55	0.05	0.22	
Pricing strategy	0.03	0.03	0.15	0.04	0.27	0.08	0.09	0.10	0.02
Appropriability strategy	0.14	0.06	0.04	0.09	0.02	0.12	0.30	0.11	0.02
Timing of entry	0.14	0.29	0.36	0.38	0.05	0.39	0.12	0.25	0.06
Marketing communications	0.08	0.09	0.07	0.15	0.27	0.07	0.30	0.15	0.03
Pre-emption of scarce assets	0.08	0.07	0.15	0.11	0.16	0.16	0.09	0.12	0.03
Distribution strategy	0.21	0.06	0.09	0.07	0.11	0.03	0.03	0.08	0.02
Commitment	0.33	0.40	0.15	0.15	0.11	0.16	0.06	0.19	0.04
Other stakeholders	0.11	0.07	0.05	0.12	0.05	0.12	0.52	0.15	
Current installed base	0.14	0.29	0.07	0.05	0.03	0.08	0.06	0.10	0.02
Previous installed base	0.02	0.03	0.10	0.03	0.05	0.03	0.06	0.05	0.01
Big fish	0.06	0.06	0.10	0.09	0.13	0.08	0.03	0.08	0.01
Regulators	0.07	0.06	0.15	0.17	0.31	0.13	0.09	0.14	0.02
Judiciary	0.07	0.06	0.10	0.09	0.10	0.13	0.09	0.09	0.01
Suppliers	0.14	0.09	0.06	0.11	0.13	0.06	0.12	0.10	0.02
Effectiveness of the standard development process	0.22	0.12	0.15	0.09	0.06	0.06	0.19	0.13	0.02
Diversity of the network	0.06	0.18	0.03	0.11	0.06	0.31	0.05	0.11	0.02
Geopolitics	0.22	0.12	0.25	0.27	0.13	0.13	0.30	0.20	0.03
Market characteristics	0.05	0.04	0.13	0.06	0.11	0.12	0.21	0.10	
Bandwagon effect	0.08	0.48	0.10	0.44	0.17	0.17	0.47	0.27	0.03
Network externalities	0.08	0.04	0.13	0.19	0.10	0.12	0.27	0.13	0.01
Number of options available	0.05	0.19	0.13	0.11	0.43	0.10	0.04	0.15	0.02
Uncertainty in the market	0.47	0.09	0.04	0.06	0.07	0.04	0.07	0.12	0.01
Rate of change	0.14	0.09	0.43	0.09	0.17	0.17	0.08	0.17	0.02
Switching costs	0.19	0.09	0.17	0.11	0.04	0.41	0.07	0.15	0.02

factor 10.". However, when GPS, GLONASS, and Galileo are compared in Table 6, it can be seen that both GPS and Galileo score similarly, while GLONASS trails behind. A cause given is the collapse of the USSR, leaving GLONASS in disarray. Currently, GLONASS does not aim to be the most advanced system, which is again reflected in the score. Galileo could overtake GPS in the near future regarding their technological superiority. Interviewees gave examples regarding the lessons Galileo learned from GPS, causing different design choices, such as a higher orbit. Another example of these design choices is stated by one interviewee as follows “It is known that radiation is a big problem and a lot of research is conducted on space “weather” because we are so dependent on the satellite infrastructure that we cannot risk to lose these satellites due to solar particle events. Galileo is well designed to sustain these effects. On the contrary, because GPS is older, the architects were less aware of the effects of radiation so Galileo profited from a longer research process.”. This shows that their technological superiority comes from their longer research process. One potential reason that GPS is still relatively ahead in the aspect of technological superiority is due to their first mover advantage (timing of entry received a score of 7 for GPS), as it has been the dominant system for well over two and a half decades. One interviewee even went as far as calling GPS “beautiful”.

Brand reputation and credibility are also important. One expert stated, "The credibility of the (GNSS) system is also important as the perception of the system can influence the user’s choice.". The literature on de-facto standardization concurs with this observation as expectations can become self-fulfilling (Shapiro and Varian, 1999) and they can be managed by, e.g., preannouncement tactics which can increase the expected installed base (Schilling, 2019). When looking at the selection of GNSS regarding brand reputation and credibility, there are vast amounts of different users and applications. These users and applications all have different requirements regarding the selection and application of GNSS, Thus, a general common denominator regarding brand reputation and credibility is hard to find. However, two related causes of this factor becoming of this importance came to light during the interviews. One interviewee stated that there is a slight patriotism factor when it comes to the selection of GNSS. Furthermore, the ability of the actors behind GPS and GLONASS to purposefully degrade their signals, due to them having a military origin, was also addressed by the interviewees. They stated that Galileo is developed with the intent for civil use, which could be one of the major drivers behind the importance of the brand reputation and credibility factor.

The factor compatibility refers to backward and horizontal compatibility. It illustrates the fitting of interrelated entities with each

Table 6
Ranking of alternatives.

Factors	GPS		GLONASS		Galileo	
	Performance score	Weighted score	Performance score	Weighted score	Performance score	Weighted score
Characteristics of the format supporter						
Financial strength	7	0.41	3	0.18	3	0.18
Brand reputation and credibility	7	0.58	3	0.25	5	0.41
Operational supremacy	7	0.73	5	0.52	7	0.73
Learning orientation	5	0.13	5	0.13	7	0.18
Characteristics of the format						
Technological superiority	7	0.58	5	0.41	7	0.58
Compatibility	7	0.54	5	0.39	7	0.54
Complementary goods	3	0.17	3	0.17	5	0.28
Flexibility	5	0.19	3	0.12	5	0.19
Format support strategy						
Pricing strategy	5	0.11	5	0.11	5	0.11
Appropriability strategy	5	0.12	5	0.12	5	0.12
Timing of entry	7	0.39	5	0.28	3	0.17
Marketing communications	3	0.10	3	0.10	7	0.23
Pre-emption of scarce assets	5	0.13	3	0.08	3	0.08
Distribution strategy	5	0.09	3	0.06	5	0.09
Commitment	7	0.30	7	0.30	7	0.30
Other stakeholders						
Current installed base	7	0.11	3	0.05	5	0.08
Previous installed base	7	0.05	5	0.03	7	0.05
Big fish	7	0.08	5	0.06	5	0.06
Regulators	5	0.10	5	0.10	3	0.06
Judiciary	5	0.07	5	0.07	5	0.07
Suppliers	5	0.08	5	0.08	5	0.08
Effectiveness of the standard development process	3	0.06	5	0.09	7	0.13
Diversity of the networks	5	0.09	3	0.05	7	0.12
Geopolitics	5	0.15	5	0.15	3	0.09
Market characteristics						
Bandwagon effect	7	0.20	3	0.08	3	0.08
Network externalities	5	0.07	3	0.04	7	0.10
Number of options available	5	0.08	5	0.08	5	0.08
Uncertainty in the market	7	0.09	5	0.06	5	0.06
Rate of change	3	0.05	3	0.05	3	0.05
Switching costs	3	0.05	5	0.08	5	0.08
Total score		5.87		4.28		5.37

other so that they can function together (Van de Kaa et al., 2011). Backward compatibility can facilitate the tapping into a previous generation of complementary goods in the form of, e.g., games (Lee et al., 2003). In various standards battles, it has been shown that this may affect standard success. Horizontal compatibility refers to the notion that competing standards are compatible through, e.g., converters such as power adapters (Van de Kaa et al., 2011). This can increase installed base of both standards. It is not mentioned that much in the previous literature that studies standards battles, but it appears to be especially important in the GNSS battle, mostly in terms of applications at a consumers level. Literature shows that as GNSS becomes multi-compatible, their functionality increases (Cai et al., 2015; Kiliszek and Kroszczynski, 2020). This compatibility between systems is furthermore addressed by one interviewee, stating that "GPS and Galileo are quite compatable, …, their base frequencies are the same, …, the developers of GNSS receivers have been able to easily include Galileo and Include GPS. They did not want different antennas for different systems.". This quote illustrates that a novel market entrant such as Galileo designed their system to fit in with interrelated entities so that they can function together.

6.2. Limitations and future research recommendations

One limitation of this study is that is does not take into account the China-owned BeiDou GNSS, which provides global coverage for positioning, navigation, and timing applications. BeiDou has been excluded due to the lack of knowledge of the interviewees on that GNSS. As the aim of this study is to unravel relevant factors related to this standards battle and assign weights to the factors, the researchers believe that by the inclusion of GPS, GLONASS, and Galileo, all relevant factors have been brought to light. Still, in the future, a follow up research could be conducted in which a similar approach is utilized and in which the BeiDou option is included. This could increase our understanding concerning factors for technology dominance in this area and also how these factors might change over time.

When compared to previous literature, a novel factor for standard dominance not previously encountered was found, 'Geopolitics'. Interestingly, that factor was mentioned to be relevant unanimously by experts and literature alike. Owning a proprietary GNSS has become vital for world powers due to several reasons. GNSS is a pervasive technology at the base of countless sectors. For clear reasons of cybersecurity, every country or political union is willing to rely on its own personal GNSS. GPS and GLONASS are military controlled systems, while Galileo is under civilian control. Moreover, the world commerce outlook is completely dependent on GNSS. The current tariff war and the establishment of a new digital silk road are some of the drivers of the future exponential growth of the sector (Radojevic, 2020). Due to geopolitics, technology may be pushed to a dominant position within the market to the extent of uneconomical proportions. GNSS's are, besides a technology used by a civilian population, also a military asset. This could have caused the factor of geopolitics to come forward within this study. However, its importance appeared to be comparatively low. Still, it was one of the essential factors within the other stakeholders category. Since this is the first time that factors for standard dominance are studied in GNSS, it is difficult to compare this result to previous studies in this specific context where the factor geopolitics might be relevant. Also, this factor is not relevant in other cases of standardization outside of this field. This limits the possibility to fully explain the non-importance of this factor for this specific case. Future research could study similar cases of standardization in which geopolitics are relevant to understand better the conditions under which this factor becomes important.

Interestingly, the experts that we consulted did not rate the factor complementary products as particularly important (it received a weight of 0.06). However, the GNSS market is expanding rapidly, which can be observed in the ever-expanding market of wearable devices, where it is common to equip these devices with GNSS chips. (Ometov et al., 2021). A leading example is the incorporation of GNSS receiver in low profile devices by Sony corporation (Sony, 2021). In light of market-based standardization, these technologies can be seen as complementary products. Therefore, we believe that in the future, experts will rate that factor to be more important. A follow up study could evaluate this proposition.

7. Conclusion

The paper studies a standards battle for GNSS. A total of thirty factors have been found relevant in GNSS standard dominance, and four of them were especially important: operational supremacy, brand reputation and credibility, technological superiority, and compatibility. Furthermore, GPS and Galileo have a high chance of becoming the dominant GNSS while GLONASS is trailing behind within this grouping of GNSS. However, the addition of other novel GNSS could change the outcome of future dominance. Still, there is a reasonable chance that all current GNSS will remain available and operational for geopolitical reasons.GPS and Galileo received similar total scores while GLONASS lags. Experts affirmed this and explained that the current status-quo in the GNSS market reflected these results. On the one hand, this provides some evidence that the BWM can let experts successfully predict the outcome of a standards battle in this arena. However, it could also be interpreted as a limitation as there is a risk of retrospective bias. Experts could have known the outcome of the standards battle, which could have affected their opinions and evaluations. Future research could study similar battles for which the outcome is unknown as of yet, and follow-up studies could study the extent to which the experts' predictions hold over time.

This study has practical implications for both policymakers and managers. Specifically, the final study outcome in which it is assessed how the technologies score on each factor is relevant in this regard (see Table 6). Practitioners can act upon these results in order to increase the chances that their technology achieves market dominance. For example, the experts believe that both GPS and Galileo score well on technological superiority and operational supremacy. However, if GPS would perform weakly on these two factors, the total score of GPS would be 5.12, and the total score of Galileo would be 5.37, meaning that Galileo would have a slight edge over GPS. Another scenario would be one where the United States military removes the GPS from consumer markets. Doing so would solidify GPS as a strategic military asset, thus removing it from the equation, and a new battle for standard dominance could ensue between GLONASS and Galileo or, even, other standards.

This research is novel in several ways. This is the first time that factors for standard dominance for satellite systems are studied. We contribute to the literature on de-facto standardization by showing that factors for standard dominance applicable in areas such as consumer electronics and information technology are also applicable to this new empirical context. By assigning weights to these factors, we provide further empirical evidence that the process of market-based standardization can be modelled, and experts can assign weights to these factors by applying the BWM, thereby contributing to prior research (Fulari and Van de Kaa, 2021; Van de Kaa, 2021; Van de Kaa et al., 2020). Furthermore, we show that, by applying the BWM, experts can better understand which technology will (according to their expert opinion) have the highest chance of achieving dominance. In this way, we add to the literature that attempts to assign weights to factors for standard dominance for various types of technological systems.

However, the contribution goes beyond replication in a new context. First, the paper provides the first empirical proof of the importance of operational supremacy for standard dominance; although seen as relevant in conceptual papers, the factor has never been found to be of importance in prior case studies (Van de Kaa and De Vries, 2015). Second, most standards battles occur in a duopolistic market where two significant players compete for market dominance with novel technology. In the battle that is studied in this paper, Galileo is a new technology introduced in a market that initially consisted of a duopoly of two dominant technologies, GPS and GLONASS. We show that while the novel technology does not necessarily provide an overall higher proposed value to its customers, it can still battle with both systems' dominant position and can even overtake the dominant position of GLONASS. Furthermore, we show that most factors for standard dominance that are applicable for a situation in which two standards are competing for market dominance are also applicable when a new standard is introduced.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

None.

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