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Open standards, closed standards or vertical integration? Interoperability pathways in markets with network effects

Sofia Rosero Abad [1,*], *Rudi Bekkers* [1], *Emilio Raiteri* [1]

[1] Department of Industrial Engineering and Innovation Sciences, Eindhoven University of Technology, The Netherlands

Abstract: Today, an increasing number of markets can be characterised as network markets. Stakeholders may feel incentives to pursue vertical integration in the value chain to achieve interoperability and to capture the network effects characteristic of these markets. Yet, technical standards offer opportunities to open such markets, cater for diversity, support competition, enable specialised roles in the value chain, and offer more opportunities for market entry. However, this might not always align with firms' strategies. This paper examines the effects of different interoperability strategies on the competitive landscape and market adoption of these technologies through four case studies: electric vehicles, game consoles, payment systems, and home computers. We find that open standards are most successful when suppliers of complementary products have sufficient incentives to participate, enabling greater competition and broader market adoption. When such incentives are weak, complementary assets are underprovided or absent, vertical integration can be effective in getting the market started, even if it might initially lead to market concentration. Over time, however, network externalities typically push firms to open critical parts of their value chains to expand their networks and benefit from a larger market. In the long run, open standards thus tend to offer the most advantageous pathway to interoperability. Their successful adoption, however, often requires strong commitment by a dominant player or through regulatory intervention to ensure the provision of critical complementary assets.

Keywords: standardisation, interoperability, market concentration, market adoption, competitive landscape, network effects

* Corresponding author:
s.a.rosero.abad@tue.nl

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Highlights:

1. This paper analyses how different interoperability pathways shape market adoption and the competitive landscape in system technologies
2. We compare open standards, proprietary standards, and vertical integration as alternative pathways to achieve interoperability in markets with network effects.
3. Using a case study approach, we find that open standards tend to foster competition and are most effective when suppliers of complementary assets have sufficient incentives to participate and expand the network
4. Vertical integration can be crucial in nascent markets with underprovided complements, but markets often evolve over time toward more open forms of interoperability.

1 Introduction

Today, markets can increasingly be characterised as system markets, composed of interdependent components and infrastructures. Large-scale adoption of emerging technologies often depends not only on their intrinsic performance but also on the availability and compatibility of complementary assets. For instance, charging networks for electric vehicles or specific software for hardware platforms are only valuable if their distinct systems and components can work together reliably. In these contexts, interoperability has become a central condition for technological diffusion and effective market functioning.

Economists and standardisation scholars have long recognised that such complementarities generate network externalities. Starting in the 1970s, a strand of literature emerged on network effects arising from the number of other users on that network (Rohlfs, 1974, 2003).[1] Examples of such networks include the Internet (of which Robert Metcalfe was a key inventor), telephone networks, and civilian CB radios ('27MC'). Later literature increasingly focuses on the network value created by complementary assets (Katz & Shapiro, 1985; Farrell & Saloner, 1986). The grounds for complementarity can be diverse. They can be grounded in technology, such as the complementarity between a computer and a printer, or between an electric car and a charging station. They can be grounded in markets, especially if they are two-sided, such as the complementarity between buyers and sellers on the eBay marketplace (Afuah, 2013). They can also be grounded in services, such as automobiles and repair services (Katz & Shapiro, 1994). They may equally arise from multiple of these dimensions at the same time, as in the case of computers and complementary software.[2] In our paper, we follow this broad, encompassing concept of complementarity, which we characterise as having a vertical interoperability character.

The literature on compatibility and standards has focused extensively on how market actors and policymakers can coordinate on common technological trajectories to avoid inefficiencies arising from incompatible systems, investment duplication, and consumer lock-in. In this strand of work, vertical complementary assets are typically treated as the domain in which network externalities are realised rather than as an object of coordination in their own right. For example, when more software becomes available for a larger compatible hardware base. Yet, the extant literature has paid limited attention to how compatible systems are created in the first place when complementary assets are underprovided or do not yet exist. In such cases, the central coordination challenge shifts from ensuring horizontal compatibility among competing products to securing vertical interoperability. That is, the ability of complementary components across the value chain to function together as a coherent system.

In this paper, we focus on how vertical interoperability in emerging system markets can be achieved through different interoperability pathways that firms may adopt, namely vertical integration, proprietary standards, and open standards. We argue that the timing and mode through which vertical interoperability is achieved have significant implications for social welfare by shaping the competitive landscape, technological uptake, and the extent to which network externalities are realised. Specifically, we examine how firms' initial interoperability strategies shape the evolution of the competitive landscape and market adoption.

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[1] These are networks of homogeneous nodes, and Metcalfe's Law (by Robert Metcalfe, who is also one of the key inventers of the Internet) proposes that the value of the network is $(N^2-N)/2$, where N is the number of users (Metcalfe, 2013).

[2] Taking these different forms of complementarities into account, Metcalfe's Law was supplemented with a range of other laws (Odlyzko's & Tilly's law, Sarnoff's law, Reed's law, Economides' law, Afuah's law), see Grillo et al. (2022) for a discussion.

To address this, we look at the historical trajectories of four technologies in which stakeholders employed different interoperability strategies. These specific cases were selected because, together, they should provide an overview of the most likely scenarios for deploying technologies with interoperability requirements. Although three of these technologies have achieved market success, the fourth case examines a technology that failed in the market despite an apparent need for interoperability. Including such failures helps us gain better insights. The cases studied are in the field of electric vehicles, game consoles, bank card payments, and home computers. By examining the dynamic landscape of key technology-based industries, we bring a fresh perspective to theoretical models on network externalities, standardisation, and market strategies.

Through our research, we observe how firms adapt their strategies as they compete for dominance and the implications this has for compatibility. Through the case studies, we find that because open standardisation allows broad stakeholder participation and reduces barriers to entry, cases that commence with such an approach almost inherently promote competitive market dynamics. However, this does not guarantee market adoption. Adequate incentives are needed to ensure complementary assets are supplied to the market, enabling greater network externalities and broader market adoption. On the other hand, in vertically integrated markets, a single actor provides all the essential assets along the supply chain. This configuration is particularly suitable in nascent markets or in markets where incentives to supply complementary assets are weak. Our cases suggest that such markets tend to open up over time, especially at points in the value chain where network externalities are significant. This, in turn, facilitates broader market adoption. Notably, even as competition emerges, the initially dominant actor is likely to retain its leading position.

By studying the effects of different interoperability strategies on the competitive landscape and market adoption, the paper addresses the complexities related to social welfare and the associated economic trade-offs. The findings in this paper can thus inform policymakers on the type of characteristics that need to be maximised (network externalities) and the associated socioeconomic trade-offs (dominant players).

The paper is structured as follows. Section 2 begins by introducing interoperability and the different pathways to achieve it. Section 3 presents an overview of the literature on the market effects associated with the various interoperability pathways. Section 4 presents the methodology used in this paper. The four case studies are described in Section 5, while Section 6 outlines how these cases reflect on the competitive landscape and market adoption of these technologies. Section 7 concludes and also discusses the limitations of our study in Section 7.1 and policy recommendations in Section 7.2.

2 Theoretical Background

In this section, we first review existing work on interoperability (Section 2.1) and then focus on the main pathways to achieving interoperability: open standards (Section 2.2.1), closed standards (Section 2.2.2), and vertical integration (Section 2.2.3).

2.1 Interoperability

Modern technologies in current industries are complex: they include many components, interact across sectors, and are part of network economies. Because most of the technologies we use today depend on the functionality of multiple other technologies and systems, interoperability[3]

[3] In this paper, we will use the terms interoperability and compatibility as interchangeably, following authors like Ritala (2012).

is essential to enable their seamless communication and interaction. With the growth of the Internet of Things (IoT) and smart technologies, the need for interoperability is expected to grow further. Acknowledging the importance of interoperability in rapidly evolving technological markets, the European Commission's Digital Agenda points to standards and open platforms to facilitate coordination (EC, 2010). This view is further reinforced in the EU's Standardisation Strategy, which highlights the role of standards in enabling interoperability, innovation and the EU's overall competitiveness (EC, 2022).

Interoperability is also essential to address grand societal challenges, which often rely on advanced, system-level technologies (Manning & Reinecke, 2016). Consider, for example, the energy transition. To use more renewable sources, the grid, wind farms, solar panels in a house, and even electric vehicles need to communicate with each other as part of a system. Interoperability among components across the value chain is a necessary condition for achieving this future.

The IEEE defines interoperability as "the ability of two or more systems or components to exchange information, and to use the information that has been exchanged" (IEEE, 1990). This requires the existence of two or more interfaces with access to information and with an information exchange mechanism (Tolk, 2024), such as access to a (technical) standard (Kerber & Schweitzer, 2017). Kerber & Schweitzer (2017) further distinguish between two types of interoperability: horizontal and vertical. Horizontal interoperability is when competing products, services, or platforms can interoperate with one another. In this case, network effects will be market-wide, minimising the risk of a strong player. Vertical interoperability, on the other hand, refers to the interoperability between complementary products.

The importance of achieving both horizontal and vertical compatibility for technology adoption has long been recognised in the literature. Building on the seminal work of Katz & Shapiro (1985), research on network industries and systems markets has shown that when a product's value depends on the availability of complementary assets—such as hardware and software, or devices and infrastructure—positive network externalities naturally arise.[4] In these settings, the utility derived from adopting a technology increases not only with the number of users adopting the same or compatible system (as in the classic telephone example) but also because compatibility strengthens incentives for third parties to supply complementary products. Much of this literature has examined the advantages and disadvantages of horizontal interoperability—how competing firms' products interconnect—and how private and social incentives can be aligned to achieve it. Katz & Shapiro (1985) emphasised that compatibility decisions shape the extent to which both direct (horizontal) and indirect (vertical) network effects can be realised. However, only a few contributions, such as Katz & Shapiro (1994), have explored in greater depth how coordination within system markets is achieved. What remains underexamined is how vertical interoperability is created in the early stages of a technology's development, and how the specific pathway chosen—whether open standards, proprietary design, or vertical integration—affects market outcomes and social welfare.

2.2 Interoperability Pathways

Recognising that there are multiple ways to achieve vertical interoperability, we differentiate among three interoperability pathways. Classified by degree of openness,[5] these pathways include open standards, closed or proprietary standards, and vertical integration. Although these

[4] Although it has also been recognized that negatives ties in a network can also invoke a reduction of positive network externalities; see Grillo et al. (2022).

[5] We refer the reader to the literature of West (2006) and West (2010) for an in-depth discussion of openness at different levels.

represent alternative routes for achieving interoperability, existing research has rarely considered them together.

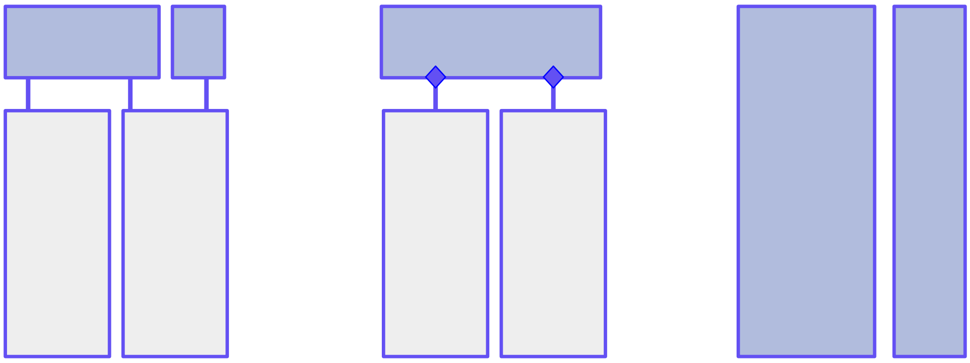
Focusing on standards, Farrell et al. (2012) describe four paths to achieve interoperability, coined ‘standards wars’ (decentralised adoption), ‘negotiations’ (negotiation in a consensus Standard Setting Organisation), ‘dictators’ (following a leader) and ‘converters’ (using converters or multi-homing). Stemming from this, Kerber & Schweitzer (2017) differentiate between horizontal and vertical ‘openness’/interoperability, and mention that interoperability is often based on access to a technical standard. The study discusses the different paths to interoperability and their associated benefits and costs. West (2010) differentiate instead between open and closed standards and analyse them in relation to economic and technical forces. Similarly, Shintaku et al. (2006) differentiate between open and closed standardisation ‘architectures’ but include vertical integration as a characteristic of the latter. Focusing on modularity, Farrell & Weiser (2003) specifically address vertical integration. The study analyses “architectures”, how they can be open or closed and how openness is in the interest of firms. It treats vertical integration as an approach for compatibility between modules and mentions standardised interfaces as one of the methods to achieve interoperability. Argyres & Bigelow (2010) also refer to standards and vertical integration in their study of product modularity, while Sanchez & Mahoney (1996) focus mainly on standardised component interfaces.

At the same time, the literature focusing on interoperability tends to look at how standards can enable horizontal interoperability (Kerber & Schweitzer, 2017) or at how different degrees of standard openness facilitate vertical interoperability (West, 2006; West, 2010; Krechmer, 2006). Since vertical integration focuses on a single firm managing the entire value chain, it is rarely considered a path to interoperability and is instead studied as a distinct phenomenon. Literature on vertical integration, therefore, focuses on topics such as its impact on firms (Stuckey & White, 1993) or on competition and welfare effects (Argyres & Bigelow, 2010; Helfat & Campo-Rembado, 2016). In this paper, we bring both these concepts together and analyse them as independent interoperability pathways,[6] each of them with their own implications for the competitive landscape and market adoption, but which can nonetheless replace one another.

For the remainder of this paper, we will focus on (1) standardisation, whether it is achieved through Standard Setting Organisations (SSOs), standard wars, or a dominant player;[7] and (2) vertical integration, whereby one firm manages the entire value chain. Figure 1 provides a stylised depiction of these pathways. Standardisation is divided into two categories depending on the level of openness: open standards and closed or proprietary standards. The following section introduces these pathways and explains how they enable vertical interoperability along the value chain.

[6] Although adapters and converters may also be used to achieve interoperability, their use is found to be costly and inefficient (Farrell & Saloner, 1992), which is why it will not be included in this paper.

[7] Such as a dominant firm or the government (Kerber and Schweitzer, 2017).



(1a) Open standards, collectively developed and unrestricted access.

(1b) Closed standards, interoperable, but a single party owns and controls the standard and rules of access (denoted by the diamond).

(2) Vertical integration, here resulting in two systems that do not interoperate

Figure 1: Stylised representation of the different interoperability pathways

2.2.1 Open standards

Open standards have been defined in various ways over time in the literature - see, for instance, Krechmer (2006) and Andersen (2008). As discussed by West (2010), openness has different dimensions, depending on whether it refers to access, control on the process, or implementation, among others. Nowadays, the broadly accepted definition for Open Standards is the one that originates from ISO (1994),[8] and subsequently formed the basis of the definitions of the Technical Barriers to Trade (TBT) Committee of the World Trade Organization (WTO) in various, slightly revised editions over time.[9] This TBT/WTO definition proposed six principles for the development of international standards,[10] which are summarised in Table 1.

Table 1: Criteria for Standards Development by TBT/WTO

Criterium	Summary
Transparency	Drafts and final standards should be easily accessible to any party, at an early stage, at a nominal fee.
Openness	Any party should be able to become a member and be given meaningful opportunities to participate at all stages of standard development.
Impartiality and consensus	Impartiality should be accorded throughout all the standards development process. This process will not favour the interests of particular suppliers, countries or regions. Consensus procedures should be established that seek to take into account the views of all parties concerned and to reconcile any conflicting arguments.
Effectiveness and relevance	Standards need to be relevant and to effectively respond to regulatory and market needs, as well as scientific and technological developments in various countries. They should not distort the global market, have adverse effects on fair competition, or stifle innovation and technological development.
Coherence	Standardizing bodies avoid duplication of, or overlap with, the work of other international standardizing bodies.
Development dimension	Constraints on developing countries, in particular, to effectively

[8] In 2019, this document was updated as ISO/IEC Guide 59:2019.

[9] These are G/TBT/1 of 1995 (WTO 1995), then G/TBT/9 review document (WTO 2000) (in Annex 4), and (WTO 2011).

[10] Although the WTO did not refer to these standards as 'open standards', that is how they have become to be known.

participate in standards development, should be taken into consideration in the standards development process

The WTO definition has also been adopted by the European Commission in its key standardisation policy documents, Regulation 1025/2012 (EP 2012), and on the New European Interoperability Framework (EIF).[11] The latter builds on the WTO principles when defining the characteristics of an open specification, particularly on transparency and openness (EC, 2017).

While it is beyond the scope of this paper to discuss each criterion in detail (for this, we refer the reader to Abdelkafi et al., 2021), we would like to highlight two dimensions related to access. Firstly, the TBT/WTO definition in itself does not set out what ‘easily accessible’ means in terms of access to standardisation documents. The European Commission, when adopting the TBT/WTO definition, further specified that it must be ‘a reasonable fee or free of charge’. Secondly, the TBT/WTO definition does not specify how access to patents or other forms of Intellectual Property (IP) should be provided, if such IP is required to implement the standard. The European Commission is again more specific here and requires that “intellectual property rights essential to the implementation of specifications are licensed to applicants on a (fair) reasonable and non-discriminatory basis, (F)RAND, which includes, at the discretion of the intellectual property right holder, licensing essential intellectual property without compensation” (EC, 2012). The FRAND regime also underpins the IP policies of almost all formal international standardisation bodies, including ISO/IEC, CEN/CENELEC, ETSI, ITU, IEEE, and many others. Likewise, the current European Interoperability Framework (see above) specifies that intellectual property rights should be licensed on FRAND terms or royalty-free (RF) to enable implementation in both proprietary and open-source software (EC, 2017).

In this paper, we focus on how open standards can serve as efficient coordination tools (Shin et al., 2015) and facilitate knowledge diffusion by making technical specifications, solutions, and methods known and accessible (Hesser, 2010). This allows a wider range of companies to develop a given technology, which, in turn, leads to more and increasingly diverse R&D efforts (Bekkers et al., 2014; Hesser, 2010). SSOs are a common avenue for developing open standards. However, open standards may also be developed by consortia or groups of firms,[12] or made open at a later stage[13]. Open standards can also be mandated by a dominant player, such as a government. Through the European New Approach, for example, the EU works with standardisation bodies to develop standards in accordance with EU legislation requirements (Bekkers et al., 2014). Open standards can be seen as valuable tools to promote interoperability and fair competition.[14] Although open standards facilitate market competition by allowing multiple producers to implement a technology, they can also delay its diffusion when conflicting interests among industry players prolong the standard-setting process. This can result in standards failing to keep pace with technological change (Meyer, 2012).

[11] Note that the original, more restrictive version of the EIF (version 1.0 from 2004) was replaced in 2010 by a version 2.0, now allowing the use of IP under specific conditions, and revised again in 2017 adopted as part of the ISA2 programme, now simply called the New European Interoperability Framework, or “New EIF” (EC,2017).

[12] Such as the CD, co-developed by Phillips and Sony.

[13] For example, the PDF or the Electric Vehicles (EV) standards from Tesla discussed later in this paper, which started as proprietary standards but became open afterwards.

[14] While standards developed in the context of the EU New Approach (also known as Harmonized standards - EN) may also contribute to interoperability, this is certainly not the case for all of them, as they often address other ‘essential requirements’ such as product safety or efficient use of spectrum resources, rather than interoperability.

2.2.2 Closed standards

Closed standards, also known as proprietary standards, are essentially those standards that fail to meet one or more of the criteria of open standards. Typically, only a few or a single company is involved. Closed standards can accelerate innovation because they do not require the consensus of multiple parties. They are also attractive to firms seeking to develop innovative products that require specific components and features. In such cases, ensuring the desired quality and safety of a product is possible only by controlling the entire value chain, including complementary products and services (Kerber & Schweitzer, 2017). Apple is an example of a company whose proprietary standards[15] enable far-reaching control, compatibility, and quality within its ecosystem (Kerber & Schweitzer, 2017). Closed standards are usually owned by one or a few firms. These firms control the development of standards and the rules regarding access to the standard specifications (Methe et al., 1998). They typically also own the intellectual property rights required to implement the closed standard and can benefit from selling the product exclusively or granting licences to third parties (Methe et al., 1998). The use of proprietary standards is argued to increase the cost of coordinating with complementary product providers (Farrell & Saloner, 1986) and to slow innovation and market growth (Farrell & Saloner, 1986; Besen & Farrell, 1994). This is due to users' concerns about making the right choice amid uncertainty about which technology will become the dominant standard in a standard war[16] (Farrell & Saloner, 1986; van de Kaa & de Vries, 2015).

2.2.3 Vertical Integration

Vertical integration occurs when interoperability across the components in the value chain is under the complete control of the dominant player. One of its advantages is that it can give a firm autonomy in decision-making. Vertically integrated firms have also been shown to be quite successful (Funk & Luo, 2015). Vertical integration is particularly popular among firms with a high degree of specificity and technological intensity (Ursino, 2015). Similar to proprietary standards, firms might opt for vertical integration to maintain autonomy over the different links of a value chain. Moreover, vertical integration allows individual companies to internalise the benefits of their products (Agarwal et al., 2007; Katz & Shapiro, 1994). Consequently, dominant firms or firms with large networks may also prefer incompatibility to avoid losing market share through the standardisation process (Farrell & Saloner, 1985; Katz & Shapiro, 1986, 1994).

In general, companies might prefer vertical integration to retain control and increase profitability (Ursino, 2015; Den Hartigh et al., 2016). Not to mention that vertical integration might be a more suitable strategy, especially when standardisation is slower (Funk & Luo, 2015). Yet, despite allowing for competition between vertically integrated silos, this configuration can also lead to a highly concentrated market.

Table 2 summarises the main aspects of the three interoperability pathways discussed above. In the Open Standards pathway, interoperability is unrestricted.[17] In the Closed Standards pathway, interoperability will depend on the (licensing) agreements made available by the firm (or firms) developing the standard, or possibly eventual outsiders that nevertheless own required patents. In the Vertical Integration pathway, there is technical alignment within a

[15] The iOS operating system, the lightning connector and the handoff feature between different categories of Apple devices are examples of this.

[16] When various firms promote competing standards, they might lead to standard wars. Once a standard establishes itself as dominant, it can become a closed standard if the winning firm maintains control over it.

[17] Unless SEP holders fail to respect the applicable FRAND or RF regime; while this aspect is relevant, it is out of the scope of our study.

single player, but no interoperability across players; all components and modules are controlled by a single firm.

Table 2: Stylised overview of the different interoperability pathways and their main characteristics

	1a. Open standards	1b. Closed Standards	2. Vertical Integration
Specifications drawn by	All interested stakeholders	One or a small group of Firms	Single firm
Access to specifications	Available to all interested parties freely or for a nominal charge	Depends on standards sponsor; may be limited to one firm or a small group of firms	Single firm
Access to patented technology required to implement the standard (SEPs)	In line with the respective SDO policy, SEP licenses must be available at Royalty Free (RF) or FRAND conditions (where the latter allows for charging licensing fees)	Free market; SEP licenses may or may not be available through (fee-based) licensing agreements	Typically, no access to required patents is provided by the vertical integrating firm
Interoperability	Interoperability is unrestricted (see text)	Interoperability depending on (licensing) agreements with the firm developing the standard	Systems do not inter-operate. All components and modules are controlled by a single firm
Speed of market introduction	May be slower, depending on how difficult it is for stakeholders to agree on important issues	Fast	Fast[18]
Variety of market alternatives	High variety	Limited variety	Limited or no variety (vendor lock-in)

3 Market effects

In markets with complex system technologies, interoperability can be attained by one of the three pathways described in Section 2.2. The interoperability pathway chosen by a firm is guided by several factors, such as the availability of complementary assets (Stuckey & White, 1993). Although interoperability pathways can evolve throughout a technology's life cycle, the pathway chosen by a firm upon entry can have long-term consequences for social welfare. In this paper, we explore these consequences, focusing on two areas: (1) the competitive landscape, and (2) market adoption.

Competitive landscape: Open standards present benefits in terms of increased competition. They increase variety through economies of scale that can bring cost advantages (Salop, 1979; Kerber & Schweitzer, 2017), facilitate cooperation between producers of complementary products (Farrell & Saloner, 1988), and give users access to a larger network (Katz & Shapiro, 1985; Markovich, 2008). Closed standards and vertical integration, on the other hand, tend to reduce competition. In these cases, incompatibility increases entry costs, especially when network externalities require a minimum installed base for the market to be viable (Katz & Shapiro, 1994; Stuckey & White, 1993). Vertical integration is thus likely to lead to the emergence of a dominant player and winner-takes-all dynamics (Den Hartigh et al., 2016), which is why it is considered to have negative welfare effects (Ursino, 2015).

Market Adoption: Open standards can positively affect technology adoption (Shintaku et al., 2006) and innovation, particularly in the development of complementary products and services (Kerber & Schweitzer, 2017). Interoperability enables broader interaction between complementary products and services by facilitating market access and technology coordination (Choi et al., 2011). However, when complementary assets are underprovided,

[18] Although most scholars agree that in a market with vertical integration, market introduction is fast, there is still some discussion about this.

especially in markets that would benefit from network effects, other interoperability pathways might be more appropriate. Proprietary standardisation, on the other hand, increases the cost of coordinating with complementary product providers (Farrell & Saloner, 1986) and slows innovation and market growth (Farrell & Saloner, 1986; Besen & Farrell, 1994). Vertical integration has similar effects on market adoption and innovation as proprietary standardisation. The literature recognises that dominant firms may seek to limit competition and slow innovation in complementary markets or suppress innovations that could threaten their long-term competitive position (Kerber & Schweitzer, 2017). However, vertical integration might be the only way to have a system in place in the early phase of development when third parties are unable or discouraged from providing complementary assets (Stuckey & White, 1993).

To better understand how firms' initial strategies affect the relationship between the interoperability pathways and social welfare, we will look at four case studies that we selected as discussed in the next section.

4 Methodology and Data

In this paper, we analyse how different interoperability pathways can affect the competitive landscape and market adoption of technologies with strong interoperability requirements. To do so, we adopt a multiple-case study approach. This approach is considered suitable, as we are analysing rich and complex phenomena (Eisenhardt, 1989). Case studies are generally considered useful for exploring new research areas (Rowley, 2002; Yin, 2009) and for familiarising with a phenomenon that can be analysed in its own context, without altering behaviour or conditions (Benbasat et al., 1987; Yin, 1994, 2009). For each case, we have identified a focal market based on its importance to the technology market and its existing interoperability challenges.

4.1 Case Selection

The cases were selected by theoretical sampling (Seawright & Gerring, 2008). We started by looking for technologies in markets with network externalities, where interoperability is achieved in different ways. Specifically, we selected cases that allow systematic observation of how different interoperability pathways influence the evolution of the competitive landscape and the extent of market adoption.

To provide a comprehensive sample, we selected two cases that were fully vertically integrated upon market entry and two cases in which open standards were used at a critical link in the value chain. In addition, we selected cases covering different industries to increase the external validity of our analysis. For each interoperability strategy, we included a case that developed within the sustainability context. The selected cases offer the opportunity to analyse how firms' initial interoperability strategies influence the evolution of the competitive landscape and the factors that determine the success or failure of these pathways in fostering market adoption.

The four case studies are in the field of electric vehicles, game consoles, bank card payment systems, and home computers; see Table 3 for details. Each case builds upon data from different sources, including academic literature, administrative documents and reports (including financial disclosures) and statistical reports. A substantive archive of sources was used to develop the main body of the cases. In the following subsection, we explain the data collection method in more detail.

Table 3: Overview of the case studies

Case study	Market / product focus	Section
Battery Electric Vehicles	Battery Electric Vehicles (BEV)	5.1
Game Consoles	Game Consoles (1970-present)	5.2
Bank Card Payment Systems at POS	Retail bank cards	5.3
Home Computers	The 1980s failed attempt of introducing a common standard, known as MSX	5.4

4.2 Data Collection

In this paper, we review the literature on four case studies from different industries. The technology markets analysed have developed at different times and over different time spans. To encompass this broad range of literature, this research follows a narrative research review approach (Turnbull et al., 2023). Narrative reviews are particularly useful for integrating insights from different disciplines (Ahmad et al., 2025). Because it is a less structured approach, it also allows the development of nuanced insights, focused on identifying those relevant to policy making (Greenhalgh et al., 2018; Uttkarsha, 2025).

The initial literature was gathered via targeted searches in academic databases and Google Scholar. To identify relevant literature, we used keywords related to each technology, combined with terms referring to the phenomena under study. These include, for example, "vertical integration", "open standard*", "closed standard*", "standard*", "value chain", "interoperability", "network effects", "network externalities", "competition", "market adoption", and "compatibility". The library of sources was later expanded through snowballing. The inclusion criteria emphasised relevance to technology development, empirical evidence, and thematic contributions. Although we did not conduct a fully systematic review, we were careful to be exhaustive in gathering our sources. Therefore, we reviewed existing literature until no more new content was found. Aside from academic literature, the reviewed material included market and technical reports, policy briefings, and self-reported facts and figures from the electric vehicle and home computer case studies. This includes data from Statista, the EC, IEA, NEN, CHAdeMO, BYD, Tesla, Elaad and SONY. To form the body of our case studies, we reviewed literature from 122 sources (Table 4). We continued to look for sources until we achieved thematic saturation. An extensive narrative of each of our case studies is presented in detail in the Appendix.

Finally, this paper focuses on two relevant market effects discussed in Section 3. Therefore, we focus on synthesising and interpreting the literature to identify trends, gaps and emerging themes (Ahmad et al., 2025) related to these two effects. In this paper, we gather this descriptive data and analyse it, focusing on the dynamic effects of the different interoperability strategies.

Table 4: Literature reviewed for the four case studies

Case study	Academic sources	Non-academic sources	Time range
Battery Electric Vehicles	25	13	2012-2023
Game Consoles	22	2	2000-2018
Bank Card Payment Systems at POS	35	7	1997-2021
Home Computers	17	1	1985-2020

5 Case Studies Narrative

This section introduces the case studies and provides a description of the contexts in which the chosen technologies were developed. Each subsection presents a brief description of the technology and the chosen interoperability strategies. A more detailed description of each case and its development is presented in the Appendix (which also includes references to all the sources we used), while the findings for each case are presented in Section 6. Table 5 provides an overview of the relevant standards for each case.

Table 5: Most important technical standards for our case studies

Case study	Most important technical standards (of any)
Battery Electric Vehicles	The IEC 62196 charging standard, defining three connection types (IEC, 2014) and the CHAdeMO connector for DC fast charging. Protocols facilitating the communication between the Electric Vehicle Supply Equipment (EVSE) and the Charge Point Operators (CPO) include the open charge point protocol (OCPP), IEC 63110, the open automated demand response (ADR), and EEBUS (Jaman et al., 2022).
Game Consoles	This case is primarily one of vertical integration, with no role for (open) standards developed by an SDO.
Bank Card Payment Systems at POS	The ISO/IEC 7813 (magnetic stripe), ISO/IEC 7816 (EMV standard for contact-based payments), ISO/IEC 14433 (EMV standard for contactless payments), and ISO 20022 (payment transaction between financial institutions, replacing the older SWIFT standard).
Home Computers	The MSX standard (”Machines with Software eXchangeability”). It was not developed by a formal SDO but by MSX Association instead, and was headed by ASCII Corporation founder Kazuhiko Nishi.

5.1 Narrative of the Battery Electric Vehicles Case

Although electric propulsion for cars dates to the late 1800s, the modern Battery Electric Vehicles (BEV) market only began to take shape in the early 2010s. At that time, no dominant design existed for the components of the electric vehicle ecosystem. Manufacturers initially adopted different approaches. Several producers launched electric models by adapting existing internal-combustion platforms.[19] These models generally offered a limited range, reflecting the constraints of platforms not designed for electrification. Only a few firms pursued fully electric platforms from the outset. The Nissan Leaf (2010) was the first mass-produced BEV built on a dedicated electric architecture. Other players, such as BYD, also introduced early BEV (e.g., the e6 model in 2010), though not yet on a fully electric platform.

A turning point occurred with the introduction of the Tesla Model S in 2012, a purpose-built, long-range electric vehicle that demonstrated performance levels comparable to gasoline cars. It appeared at a time when the sector lacked mature charging systems, defined interfaces, and widespread charging infrastructure. Because these complements were underprovided (or simply did not exist), Tesla delivered a vertically integrated solution—vehicle, charging infrastructure, and customer interface— and de-risked adoption for early users. It also set technical benchmarks for range, charging speed, and user experience that combustion-adapted models struggled to match. As BEV adoption grew, manufacturers increasingly shifted away from combustion-based adaptations toward dedicated electric platforms.[20] In parallel, the sector

[19] Examples include the Ford Focus Electric (2012), the Fiat 500e (2013), the Kia Soul Electric (2015), and the Volkswagen E-Golf (2014), all of which repurposed conventional vehicle architectures by replacing the combustion engine with batteries and electric drivetrains (see Appendix A).

[20] For example, Volkswagen's MEB, Hyundai/Kia's E-GMP, Mercedes' EVA, and the Renault/Nissan/Mitsubishi CMF-EV.

progressed from an initial period with no shared technical specifications to the gradual emergence of standardised solutions for connectors, charging interfaces, and communication protocols, enabling greater compatibility across vehicles, chargers, and service providers.[21] Over this period, Tesla's early success demonstrated the viability of long-range BEVs and contributed to accelerating adoption, as reflected in the rapid growth of global BEV stock (Figure 3 in Section 6.1). As more firms entered with fully electric platforms, industry-wide standardisation was progressively achieved, and Tesla itself, after initially relying on proprietary solutions, also adopted these open standards, including shifting to CCS in Europe and maintaining compatibility with CHAdeMO in the US. More recently, it also opened the proprietary charging standard (NACS), extending access to the supercharger network to non-Tesla users. This transition marked the shift from early experimentation to a more structured, mature phase of large-scale electrification.

5.2 Narrative of the Game Consoles Case

Game consoles are dedicated computing devices designed specifically to run video games on a television or display. Unlike general-purpose computers, consoles operate as closed systems, with hardware, operating system, and user interface tightly integrated and built around proprietary standards defined by the platform owner. Video game consoles entered the consumer market in the late 1970s as self-contained products, each with its own proprietary ecosystem. Early consoles typically incorporated a single game, but the industry changed with the introduction of programmable, interchangeable cartridges, first released in the Fairchild Channel F. From that moment, the commercial success of a console increasingly depended on the breadth and attractiveness of its game library. Initially, console manufacturers developed game software internally, as part of a fully vertically integrated solution. However, expanding the installed base required the involvement of third-party developers. Early licensing agreements with game developers were highly restrictive and favoured the platform owner, who controlled access to the proprietary system. Exclusivity was common until a 1992 antitrust ruling reduced its use (Lee, 2013); yet strong licensing remained important to subsidise hardware sales.

Over time, the decisive competitive factor in the sector became the size and quality of each platform's video game library, a key complementary asset that generated strong network effects. A console with more (attractive) titles drew more users, which in turn attracted additional third-party developers, leading to a self-reinforcing cycle. Building such libraries required a mix of favourable agreements with third-party developers and continued internal development and vertical integration, as illustrated by Sony's reliance on proprietary standards combined with first-party game production and its own digital distribution channel. Platforms unable to assemble a sufficiently large or attractive catalogue gradually disappeared from the market. As a result, the number of console manufacturers fell sharply, as shown in Table 7 in Section 6.2.

5.3 Narrative of the Bank Card Payment Systems at POS Case

Payment services at the Point-of-Sale (POS) require a high degree of interoperability: merchants must be able to accept payments from any customer, regardless of their bank, card brand, or country of origin. More broadly, the viability of any POS payment technology depends not only on the payment instrument used by consumers but also on the widespread adoption of payment terminals capable of recognising and processing that instrument. These terminals function as the essential complementary asset in the POS value chain: without

[21] See Table 5 for an overview of the standards in question.

merchant uptake, no payment method—regardless of its technical merits—can achieve scale or generate network value. Over time, POS systems evolved through several technological generations—stored-value cards (SVC), magnetic-stripe (magstripe) cards, and later contact and contactless smart cards. Magstripe systems achieved broad adoption through the ISO/IEC 7813 standard, an open specification that ensured interoperability across banks, card issuers, and merchant terminals. Despite global adoption, it started to be increasingly viewed as insecure by the early 2000s. To combat fraud, many jurisdictions transitioned to EMV-compliant chip cards, a global specification for secure contact and contactless payments based on ISO/IEC 7816 and ISO/IEC 14433, respectively.[22] Europe was an early adopter of this standard: the EU required EMV-based cards and terminals by 2010. A liability shift further encouraged upgrades, making merchants responsible for fraud occurring on non-EMV terminals. Adoption elsewhere was much slower, particularly in the United States, where neither regulation nor liability provisions pushed the use of EMV terminals. The diffusion of contactless cards followed a similarly uneven trajectory. Although NFC technology existed by 2002 and pilots began in 2007, widespread adoption lagged. Central and Eastern European countries, especially Poland, became early leaders, supported by large-scale card migration and POS upgrades driven jointly by the banking sector and public-sector programs. Other countries, such as the Netherlands, introduced contactless cards only in 2015, while Belgium and Germany saw very low usage until external shocks, such as the COVID-19 pandemic, accelerated adoption.

5.4 Narrative of the Home Computers Case

Although the market for home computers emerged in the early 1980s, these devices differed markedly from modern personal computers. Home computers were affordable, TV-compatible machines intended for domestic use. They typically combined the CPU and keyboard into a single unit, running a ROM-based operating system and supporting basic programming, text editing, and games. Unlike business-oriented machines, home computers targeted households and hobbyists. Technically, the early home computer market was highly fragmented. Each manufacturer developed its own operating system and peripheral hardware, such as printers, joysticks, and tape formats. For users, this created substantial risk: buying the wrong machine could leave them with a device that soon lacked software support or was orphaned entirely (examples include the Sinclair QL and the Commodore Plus/4 home computers, both from 1984). From the user’s perspective, this meant investing in equipment without a guarantee of its long-term functionality or success. Against this backdrop, the MSX standard was introduced in 1983 as an attempt to provide an open platform for the development of both software and hardware. Originally developed by Microsoft and ASCII, its standardised architecture, based on the Zilog Z80 processor and a universal cartridge slot, aimed to attract third-party developers to supply complementary products. Indeed, several firms—including Panasonic and Yamaha—began offering specialised complementary components, such as word-processing tools or music synthesiser hardware. While technologically sound, MSX lacked participation from major home-computer players such as Commodore, Sinclair, and Atari, and it failed to penetrate the American market, with most of its sales occurring in Japan. At the same time, the emergence of more powerful 16/32-bit computers and IBM-compatible PCs eroded MSX’s competitive position, resulting in MSX failing to reach the installed base required for network effects to materialise. Although new generations of MSX were released (MSX2, MSX2+, and TurboR), industry support diminished, and MSX production ended in 1995. The market consolidated around IBM-compatible PCs, which absorbed many of the firms once involved in MSX.

[22] EMV is a 1990s initiative taken by Europay, MasterCard and Visa, set to replace magstripe technology (van den Breekel et al., 2016).

6 Case Study Findings

In this paper, we departed from the assumption that the timing and mode through which vertical interoperability is achieved have significant implications for social welfare by shaping the competitive landscape, market adoption, and the extent to which network externalities are realised. To explore this, we examined four case studies to analyse how firms' initial interoperability strategies influence the evolution of the competitive landscape and market adoption. Table 6 summarises the findings for each of the two dimensions we analysed; below, we discuss each case in greater detail. Again, references to sources are offered in the appendix.

Table 6: Main results from the case studies

Case study	Interoperability strategy		Competitive landscape	Market adoption
	Initial	Current		
Battery Electric Vehicles	Vertical integration	Vertical integration and open standards	Initially a niche market. Open standards allow competition, but Tesla maintains a strong position.	Once a niche market, EV sales now account for 20% of total vehicle sales worldwide, half of which are BEVs (IEA, 2025). Availability of a larger charging infrastructure increased incentives for consumers.
Game Consoles	Vertical integration	Vertical integration and proprietary standards	Hard to enter the market because each entrant must build their own platform. Original Equipment Manufacturers (OEMs) such as Sony have the dominant position. For each successive generation there are fewer players.	After initial growth, the market eventually declined: the overall market size in terms of hardware unit sales of the latest generation (which includes the PS4) has dropped compared to the fifth generation (which included the PS2).
Bank Card Payment Systems at POS	Open standards	Open standards	Highly competitive market	Large adoption associated with availability of infrastructure and security reasons.
Home Computers	Open standards	Open standards	MSX allows competition of hardware and software suppliers.	Lack of adoption of MSX likely related to the quality of the complementary products and overall functionality.

6.1 Findings of the Battery Electric Vehicle Case

In the BEV market, there are at least three critical levels where interoperability must be achieved. These three levels are: (1) between components and the assembled BEV, where safety and the ability for interoperability play a pivotal role; (2) between the BEV and charge points, focusing specifically on the charging plug and associated protocols, which may also include Vehicle to Grid (V2G) functions; and (3) between charge points and the mobility service/electricity grid, allowing the user access to different charging stations while only having to subscribe to one service provider, similar to the 'roaming' concept in mobile telecommunications. In this case, the most relevant open standards for our analysis are those related to the charging protocols, such as IEC 62196-3 (connectors), IEC 61851 (charging), and IEC 15118 (communication).

Interoperability strategy: BEV entered the market as a niche technology, forcing the early entrant, Tesla, to develop all essential components and interfaces for vehicle use. Consequently, Tesla adopted a vertically integrated strategy, covering the critical interoperability layers (vehicle components, vehicle-to-charger interfaces, and charger-to-service-provider communication) to ensure system-wide compatibility in the absence of established standards or third-party suppliers. However, as the market developed, there was a move towards open standards. First, thanks to the availability of other open standards such as CCS and CHAdeMO; and second, thanks to Tesla opening access to its charging specifications. This move enabled other players to participate. Figure 2 illustrates the main value chain components (a), how they were provided upon market entry (b) and how they are currently provided (c).[23]

Competitive landscape: This case illustrates that when complementary assets are lacking, vertical integration is the only way to achieve alignment. Although vertical integration is usually associated with negative consequences on market concentration, this case shows its importance in enabling the roll-out of technologies that would otherwise be unable to enter the market. In this case, the market eventually transitioned towards the use of open standards in certain links of the value chain. This increased competition, as new players could enter the market. Nowadays, important players also include BYD, Volvo, Volkswagen, and SAIC, which sell on the global market using the GM brand, among others (Statista, 2025).

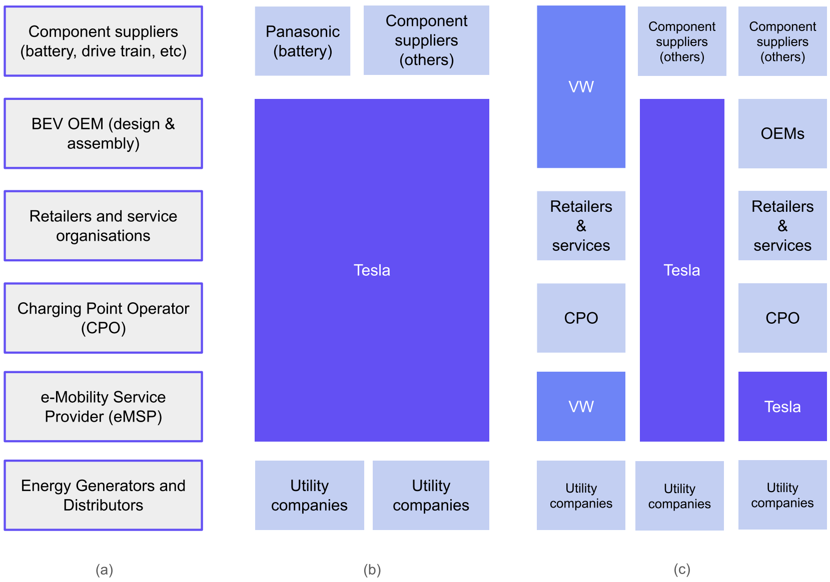


Figure 2: a) BEV value chain components; b) Value chain in the initial period (2012); c) Stylised representation of the current value chain.

Market adoption: In the early stages of the BEV market, vertical integration played a decisive role in enabling market adoption. By internalising complementary assets, Tesla could guarantee system-wide functionality and offer early consumers credible commitments regarding usability and range. This ensured the technology's basic viability at a time when no external suppliers or infrastructure existed, solving a problem that would otherwise have prevented adoption.

However, despite its initial vertical integration strategy, the market eventually moved towards open standards. Thanks to this, users acquired access to a larger network of charging stations, making the use of electric vehicles more attractive. This accelerated technology adoption and the realisation of the full potential of the network effects. Although opening these specifications reduced Tesla's market share, overall market expansion was observed, as shown in Figure 3.

[23] Based on data from Nieuwenhuis (2018); Chen & Perez (2018); Klapwijk & Driessen (2016).

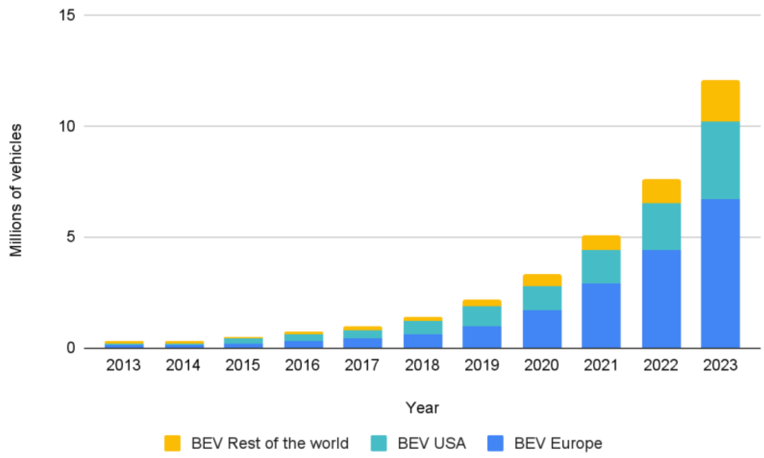


Figure 3: Battery Electric Vehicle (BEV) stock. Based on data from IEA (2024).

6.2 Findings of the Game Consoles Case

Game consoles require interoperability at various levels: (1) in the form of APIs and software libraries, (2) technical specifications for hardware elements, optical storage on a CD or DVD, and (3) telecommunications in the case of online gaming services. End-users' high expectations for new games mean that all actors are working at the frontiers of what is possible, while also requiring interoperability. However, there are no open standards at the most critical points in the value chain, only proprietary standards closely controlled by the platform owner. Network effects are thus also vertically managed. In a game console, network effects are present in various ways: through the availability of (high-quality) games, the number of other users with which the game can be played, complementary hardware such as controllers and VR glasses, etc.

Interoperability strategy: In this case, market players initially opted for vertical integration strategies upon entering the market. As in the BEV case, each player developed all the components along the value chain with their own unique features and design preferences. Eventually, firms opted to use proprietary standards to allow third-party game developers to participate and thereby expand their game offerings. Nintendo, Sony, and Microsoft all have their own proprietary APIs, which are often NDA-restricted. For Microsoft, for example, DirectX is NDA-restricted for Xbox game development but not for PC game development. Figure 4 illustrates the main components in the value chain (a) and how these are organised among the current market players (b).

Competitive landscape: Because each console generation relied on closed, proprietary standards with no horizontal interoperability between competing systems, the market repeatedly converged on a small number of dominant platforms. As shown in Table 7, the number of console manufacturers fell from 27 in the first generation to only 3 manufacturers in the current, eighth generation. This contraction mirrors the strategic importance of assembling the large and attractive game library, which Figure 5 shows consistently predicts the winning platform in each generation.[24] The absence of open standards eliminated the possibility of cross-platform compatibility, increasing entry barriers and creating winner-takes-most dynamics. Consequently, the interplay between proprietary interoperability pathways and strong network effects led to the highly concentrated market observed today.

[24] Based on data from VGChartz (2022) and Statista (2024).

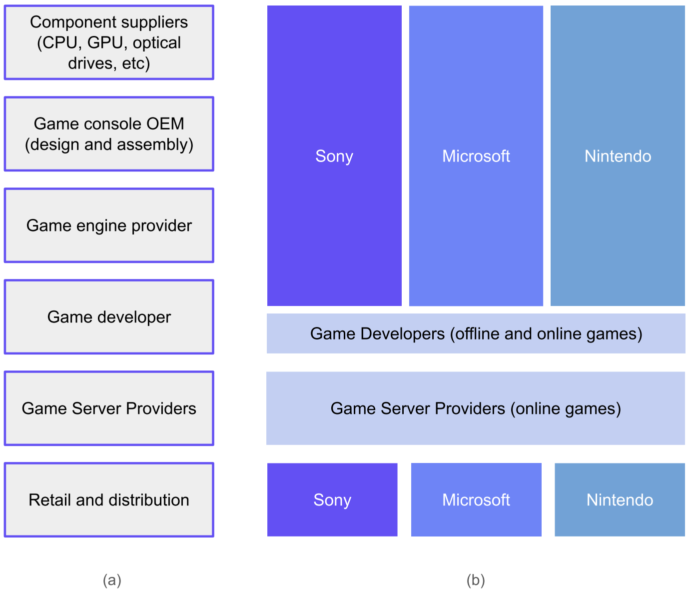


Figure 4: a) Stylised representation of a game console's value chain components; b) Organisation of the value chain components of existing market players.

Market adoption: In this market, the successful firms' strategies relied on two factors: control over the value chain and the development of the right incentives for the provision of complementary assets. For example, through the development of (favourable) agreements with third-party developers. In this case, a virtuous cycle developed, in which platforms with the largest game libraries could reach a larger market, which in turn increased incentives for game producers. Therefore, while winning platforms kept growing, firms that failed to attract (popular) game developers eventually exited the market (Table 7).[25]

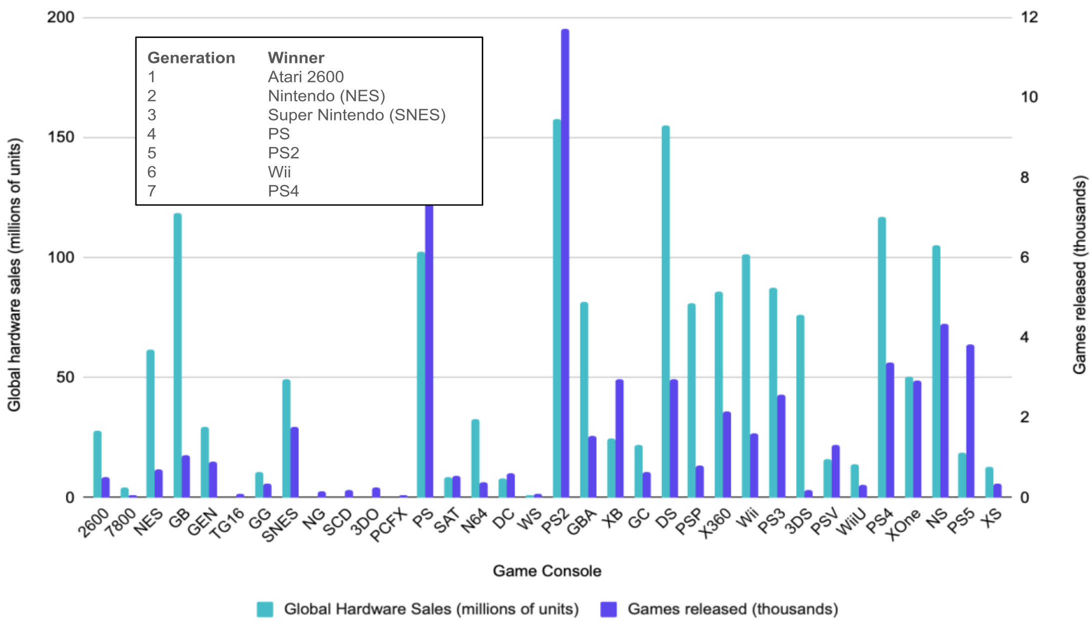


Figure 5: Global hardware sales vs. number of games released/available for the corresponding platform.

[25] Based on data from Gretz (2010); Wikipedia (2021).

Table 7: Number of game console manufacturers per generation.

Generation	Period	Number of manufacturers
First	1976-1984	27
Second	1985-1988	17
Third	1989-1993	16
Fourth	1994-1999	15
Fifth	2000-2005	10
Sixth	2006-2012	8
Seventh	2013-2020	3
Eighth	2021-present	3

6.3 Findings of the Bank Card Payment Systems Case

In payment services, interoperability is required at the following levels: (1) for technologies at bank card level, e.g., swipe, chip, contactless, (2) for security systems protecting bank-to-bank and bank-to-customer transactions, (3) between the financial institutions in order to transfer money between bank accounts and (4) between banks (or acquirers) and card brands, for instance to register transactions and check whether payment limits have been reached.[26] The most relevant standards for our analysis are ISO/IEC 7816 and ISO/IEC 14433, for contact and contactless cards, respectively.

Interoperability strategy: In this case, a small group of private actors coordinated to develop a common technical framework for secure card payments, eventually formalised as the EMV standard. The main objective of this process was to reduce increasing fraud associated with magnetic-stripe transactions and to ensure global interoperability across banks, acquirers, and merchants. The development of EMV relied on formal standardisation developed for ISO/IEC 7816 and ISO/IEC 14443, with participating organisations settling on shared specifications for secure chip use and terminal compatibility. Because these specifications were openly documented and available to any issuer or terminal manufacturer willing to comply, the standardisation process created an effective interoperability pathway for the industry to migrate from insecure legacy technologies and towards a globally interoperable environment. Figure 6 presents the main components of the value chain (a) and how these interact to achieve interoperability (b).[27]

[26] Standards for smart-card-based electronic payment systems and for the security of online payment systems are also being discussed in the industry (Asokan et al., 2000) but they are out of the scope of this paper since they do not apply at POS.

[27] Based on data from Au & Kauffman (2008); Agarwal et al. (2007); Kadhiwal & Zulfiquar (2007); Khan et al. (2017); Asokan et al. (2000); Leinonen (2001).

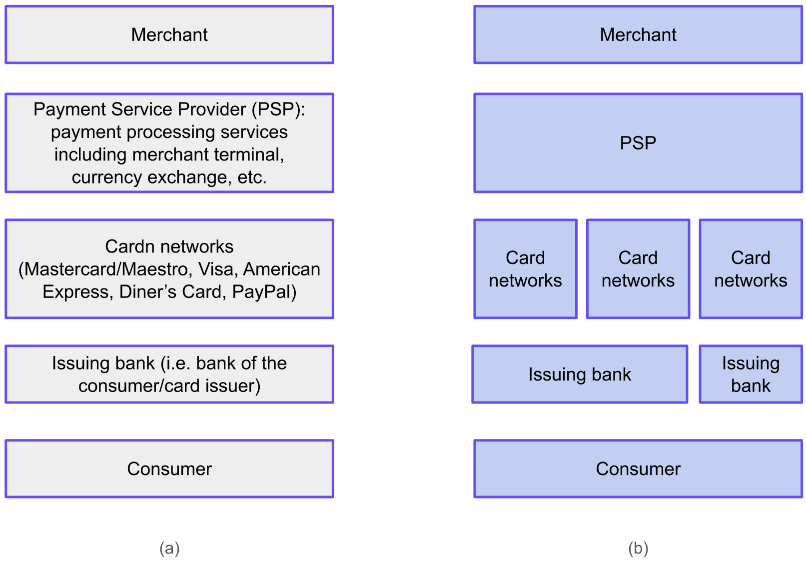


Figure 6: a) Stylised representation of the value chain components of Payment Systems at POS; b) Possible forms of interoperability between value chain components.

Competitive landscape: This case shows how the use of open standards facilitated market participation for both card providers and vendors at points of sale (POS). As an open standard, it allowed other card providers to adopt the specifications and enabled the deployment of compliant infrastructure. Initially, alternative card payment technologies were available (such as magstripe cards). While both payment methods remained accepted in North America, regulatory intervention in Europe led to the replacement of magstripe cards with EMV-compliant cards. The openness of the standard also made it easier for new players such as PayPal, Apple Pay, and other digital wallets to plug into the existing infrastructure. As a result, competition remained broad and focused on services, fees, and performance rather than being shaped by incompatible proprietary systems.

Market adoption: In this case, adoption has been influenced by various factors. Although EMV standards could be easily adopted by card providers, they also required the deployment of compatible infrastructure at POS, and user acceptance. In the EU, regulatory requirements and a shift in liability accelerated this transition,[28] ensuring a rapid rollout of EMV-compliant infrastructure. This effect was particularly visible in Eastern European countries, where coordinated national programs and strong issuer–merchant incentives led to some of the fastest adoption rates worldwide. As shown in Figure 7, these countries moved quickly toward near-universal uptake of contact and contactless EMV terminals in a short time span, illustrating how the combination of open standards, clear incentives, and targeted regulatory support can rapidly scale a payment technology. In contrast, markets without similar regulatory pressure, such as the United States, experienced much slower adoption despite the availability of the same technical standard.

[28] Major card networks initiated the liability shift to make the stores and shops at POS liable for fraudulent actions resulting from transactions in non-EMV supporting terminals (Bouzefrane, 2009). This liability shift was introduced to incentivize merchants to upgrade to EMV-compliant POS hardware.

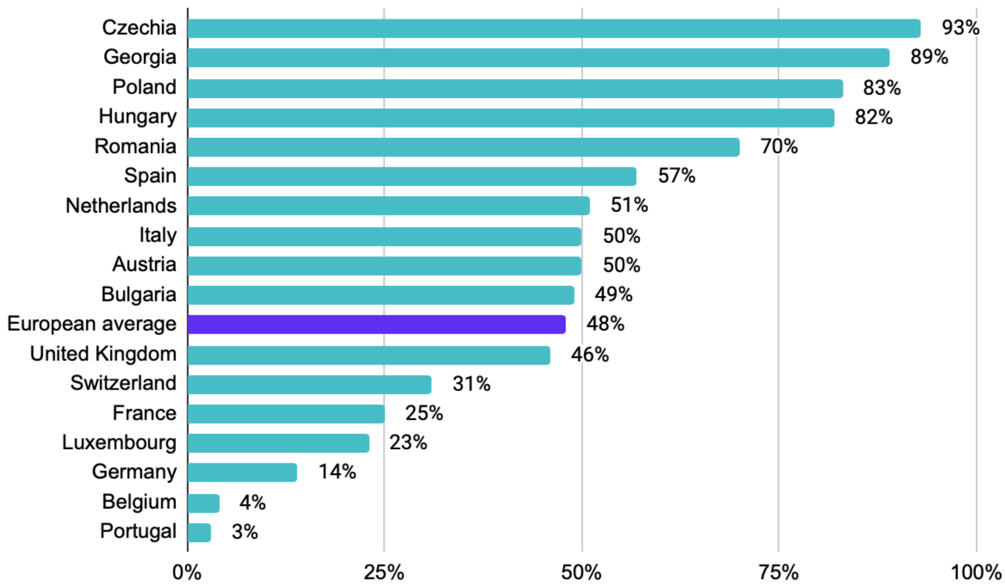


Figure 7: Share of Contactless Payments Transactions at POS in European Countries in 2018. Based on data from Statista (2018).

6.4 Findings of the Home Computers Case

In the case of home computers, interoperability is required between (1) the computer OEM and the software used to drive the hardware, and (2) the hardware platform and the peripheral products. Without software compatibility, the computer's functionality was seriously diminished: people had to write their own code in BASIC, the programming language common to home computers at the time. Before MSX, a very common form of differentiation in this market and a way to distribute high-performance software (especially games) was by means of hardware expansion cartridges slotted into the computer. The MSX standard tried to address this by enabling hardware and software compatibility.

Interoperability strategy: In this case, we focused on the strategy taken by MSX on the home computer market. MSX was developed with the intention of opening participation of third party software and hardware developers supplying to the home computer market. Figure 8 shows the main components of the home computer value chain (a) and how these could be organised with the MSX standard (b).

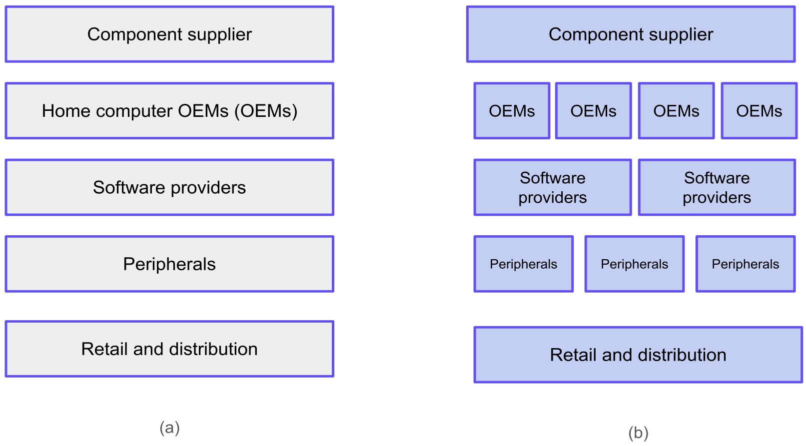


Figure 8: a) Stylised representation of the value chain components of a Home computer; b) Possible forms of interoperability for Home Computer components in the 1980s.

Competitive landscape: Although MSX was designed as an open architecture and initially attracted a relatively large group of hardware producers (including Yamaha, Panasonic, Toshiba, Philips, Sanyo, and several smaller Japanese and European firms), the openness of the platform did not translate into a competitive or sustainable ecosystem. Dozens of MSX-compatible models were released in the early years, covering a wide range of price points and features, and the standard enabled a variety of peripheral devices and specialised expansions. However, MSX failed to provide a top-quality product and to attract popular third-party developers. Since MSX was designed with an open architecture, it opened the market to game developers and word processing developers alike. However, the supplied software lacked the quality of specialised developers in the game and personal computer markets. Eventually, other specialised vertically integrated platforms were more successful in the market, which soon became characterised by higher concentration.

Market adoption: This case shows that while open standardisation is designed to open up the market, it is more successful when incentives for the production of complementary assets are present. In the MSX ecosystem, these incentives were weak: major game developers did not support the platform, software quality lagged behind competitors, and most sales remained confined to Japan with very limited penetration in the U.S. and only modest uptake in parts of Europe. At the same time, the rise of more powerful 16/32-bit machines and IBM-compatible PCs quickly outperformed MSX systems. As a result, the installed base never reached the scale needed for network effects to take hold, and industry support declined across later generations (MSX2, 2+, TurboR), leading to production ending in 1995.

This case thus illustrates how, without adequate incentives, the network cannot develop, and technology adoption cannot be guaranteed. It also shows how vertically integrated firms may be better suited for the provision of specialised, technology-intensive products, even though this may result in market concentration upon market entry.

7 Conclusions

In this paper, we present four cases to gain insights into how firms' initial interoperability strategies influence the evolution of the competitive landscape and the market adoption of complex system technologies.

The insights from these cases have led us to the following main conclusions. First, we observe that, from the various interoperability pathways, open standards are the most likely to foster competition. Depending on the setting, regulation may be required to set the market direction and avoid fragmentation, as illustrated in the payment system case. The other pathways, vertical integration and proprietary standards, were found to raise the costs of market entry by requiring new players to develop all components of the value chain. We note, however, that vertical integration may at times be the only viable entry strategy, as illustrated by the BEV case. This case further shows that markets tend to evolve toward more open, interoperable pathways, which, in turn, lower barriers to new entrants. Nonetheless, our findings indicate that the initial dominant actor is likely to retain a leading position even as the market opens to increased competition.

Second, we observe that open standards can promote market adoption, provided that suppliers of complementary assets are present, and that there are sufficient incentives to participate in the market. In the Battery Electric Vehicle case, for example, a move towards open standards allowed the development of complementary charging infrastructure. By expanding network externalities for BEV users, this move helped drive increased market adoption of BEVs. On the other hand, the Home Computers case is characterised by weak incentives to supply complementary assets. Namely, the performance of the complementary assets provided was below that of the average competitor. Market adoption of MSX was therefore limited, leading to its eventual failure.

Overall, we find that open standards are particularly useful in markets seeking to ensure competition in the complementary asset market. However, market adoption requires incentives for developing these assets and adopting a specific solution. In these cases, regulation can provide the market with these incentives. On the other hand, we find network externalities to be a strong incentive for firms to move towards open forms of interoperability (i.e. open standards). This enables greater market adoption and, although it leads to the entry of competitors, dominant parties are likely to maintain their leading position.

Our cases illustrate a strong need for complementary goods at all stages in the creation of an industry, even in the earliest stages: For instance, in the Battery Electric Vehicle case, drivers needed charging stations in order to make longer trips, and in the Game Console case, they were important in the early phases to ensure a wide and diverse offer of games. Open standards can increase the availability of such complementary goods through network externalities (but this assumes the network is already of sufficient value to attract others to supply complementary goods). For vertically integrated systems, the supply of complementary goods is not self-evident, but the vertically integrated firm itself can address such a void and provide for such goods by itself (as Tesla did by rolling out its own charging infrastructure, or the early game console makers by creating their own games or paying others to do so). While costly, they can do so even if the network has not yet reached a high value.

Brought together, our cases illustrate that while open standards offer the most opportunities for competition, network expansion and technology adoption, they are not always the most suitable strategy. Vertical integration may be better suited for the provision of specialised, technology-intensive products, particularly when these are necessary to get the market started. Integration is also the only strategy for firms entering niche markets in which complementary products and infrastructure are not yet available. Therefore, although vertical integration might (initially) result in market concentration, this needs to be weighed against the possibility of lacking the technology (e.g., BEV) or having an underperforming alternative (e.g., MSX). Notably, our cases show that even when vertical integration is initially adopted, the market may open up later to allow network externalities and increase adoption.

As a final note, our work may also raise the question of whether standardisation scholars should consider vertical integration not just as a path for interoperability, but as a form of standardisation. While this is one possible interpretation of our findings, our results suggest a more cautious view. Because the repeated use of a solution by different stakeholders is such a fundamental aspect of standardisation, vertical integration should remain conceptually separate from the dichotomy between open and proprietary standards.

7.1 Limitations and Future Research

In this research, we aimed to increase external validity by including technologies from different markets, enabling us to study various interoperability strategies upon market entry. However, this implies that each of these technologies develops in markets with different dynamics. For example, the game console market in the entertainment industry is about non-essential goods, whereas bank card payments are essential to the economy. As such, decisions to support the market adoption of a technology have different motivations and incentives guiding its success. To avoid these biases, future research could look at technologies in similar markets.

Because most of these system technologies relate to IoT and smart devices, future research could also focus on technologies designed to address grand societal challenges. In particular, on the trade-offs that become necessary when focusing on technologies with a welfare component. Although our research does not delve in depth into these scenarios, the case of electric vehicles already shows that certain societal benefits (such as air quality or sustainable mobility) may be pursued more effectively by a dominant party. Regulatory intervention can be helpful later, once the technology is mature and established. Consequently, it would also be interesting to investigate the managerial strategies that firms pursuing technological solutions to grand societal challenges could adopt.

To test our findings, future studies could also address our question empirically. For example, by observing the changes in the market concentration levels through time and their relation with the number of patents or innovation expenditure in a given sector. Such a study would allow for generalisation on a larger scale.

7.2 Policy Recommendations

In this paper, we explore how the adoption of (open) standards impacts the competitive landscape and market adoption of technologies in industries characterised by network externalities. Our findings have relevant policy implications.

First, the paper illustrates that temporary monopolies, such as the near-monopoly Tesla enjoyed in the early BEV market, can be beneficial for getting a market started and for pushing other companies to raise the bar and innovate to a much higher degree than they would have otherwise. The main question for a policymaker is whether a temporary monopoly can lead to a more competitive market over time or to a long-term monopoly, something often feared in the context of 'big tech' companies. Our work illustrates that the former is indeed possible, for instance, by mandating the use of technical standards and thus opening up markets and competition. This was seen in the BEV case when the European Union mandated the use of the CCS Type 2 charging standard, leading Tesla to adopt a more open strategy and, eventually, to increased competition from other car manufacturers. Given that such a course of events is not guaranteed, further work could provide better insight into the opportunities and risks of using standards in this way.

Second, although open standards cater for a competitive landscape, they can also lead to fragmentation. In these cases, regulations are necessary to steer the market and innovative efforts in one direction. We find that regulation can steer firms towards compatibility and provide guidance to users and consumers alike. This is illustrated in the payment systems case. While legislation facilitated the adoption of EMV technology in the EU, in the USA, different systems remain available simultaneously.

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Contributor Statement

Sofia Rosero: Conceptualisation; Formal analysis; Investigation; Methodology; Resources; Roles/Writing - original draft; and Writing - review & editing. Rudi Bekkers: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Writing - original draft; and Writing - review & editing. Emilio Raiteri: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing - review & editing.

Use of AI

During the preparation of this work, the author(s) used ChatGPT in order to improve the readability of the text, and M365 Copilot in order to create the thumbnail. After using this tool/service, the author(s) reviewed, edited, made the content their own and validated the outcome as needed, and take(s) full responsibility for the content of the publication.

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Conflict Of Interest (COI)

There is no conflict of interest.

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Appendices

The case studies discussed in Sections 5 and 6 draw on extensive research into developments within their respective markets and the factors that shaped key decisions. The appendices below present those case studies in full detail.

Appendix A: Battery Electric Vehicles (BEV)

Our first case focuses on emission-free mobility by analysing EVs. We focus specifically on BEV, which are those powered solely by an electric battery. Coined "Early Pioneer Advantage", this case involves a greenfield situation where a pioneer makes the first move.

A1 Scope for interoperability

In the BEV market, there are at least three critical levels where interoperability must be achieved. These three levels are: (1) between components and the assembled BEV, where safety and the ability for interoperability play a pivotal role; (2) between the BEV and charge points, focusing specifically on the charging plug and associated protocols, which may also include V2G functions; and (3) between charge points and the mobility service/electricity grid, allowing the user access to different charging stations while only having to subscribe to one service provider, similar to the 'roaming' concept in mobile telecommunications. Therefore, stakeholders' decisions regarding the interoperability strategy are mostly related to these three levels.

A2 Interoperability and market dominance

Although the concept of electric vehicles dates to the 1800s, the BEV market only took off with Tesla. Often portrayed as the pioneer and market leader in BEVs (Chen et al., 2019; Moritz et al., 2015), Tesla was the first to design a fully electric vehicle from scratch, at a time when other companies were trying to adapt existing combustion engines.[29] Certain aspects differentiate Tesla from other companies. Tesla was the only one to give its Model S an autonomous-driving range comparable to that of a gasoline car, while the others had much lower ranges.[30] Examples of BEV without a fully electric platform include the Ford Focus Electric (2012): 76 miles, Fiat 500e (2013): 87 miles, and Kia Soul Electric (2015): 93 miles (Thomas & Maine, 2019; USEP, n.d.). Tesla also implemented far-reaching vertical integration, for instance, by setting up its own charging network and integrating the retail network. Furthermore, Tesla focused its entire business on the electric platform, whereas for Nissan and General Motors, BEVs were diverging side activities. Given these unique aspects, we feel it is appropriate to consider Tesla as the main pioneer in this field for our case study. Furthermore, although the Nissan Leaf was the first fully electric vehicle on the market, its sales never reached those of Tesla (Argonne, 2022), making it hard to assume that significant market changes resulted from Nissan's role.

With no dominant design for batteries and charging systems, it was difficult for the electric car industry to develop and evolve (Brem et al., 2016). In this context, Tesla entered an infant market with no standards, specifications or suitable BEV components. This was one of the main reasons for Tesla's vertical integration (Thomas & Maine, 2019; Zarazua de Rubens et al., 2020; Nieuwenhuis, 2018). Even when important components were outsourced, such as the battery pack to Panasonic (Chen et al., 2019), this was according to Tesla's technical specifications. Tesla also adopted a fully vertically integrated business model, including retail, distribution, and maintenance and repair through its own sales outlets (Nieuwenhuis, 2018; Crane, 2015), despite strong opposition from the Big Three US auto manufacturers (Crane, 2015). In addition, it developed its own roadside charging infrastructure, known as 'superchargers' (Chen et al., 2019; Long et al., 2019), which charge vehicles to 50 per cent in only 20 minutes (Tesla, n.d.), and it is only available to Tesla drivers. Tesla's various forms of vertical integration provided a high degree of control and enabled relatively fast implementation, independent of others' decisions. Initially, other vehicle manufacturers took a very different route. They mostly chose existing Internal Combustion Vehicles (ICV) platforms and replaced the combustion engine with batteries and electric drive trains (Chen et al., 2019), as was the case with the Ford Focus Electric (2012), the Fiat 500e (2013), the Kia Soul Electric (2015) or the Volkswagen E-Golf (2014), among others. If they developed a BEV on a fully new platform, it was usually a niche product. Only recently have large carmakers changed their strategy and announced true electric platforms, such as the Volkswagen Group MEB, the Hyundai/Kia E-GMP, the Mercedes EVA, and the Renault-Nissan-Mitsubishi alliance CMF-

[29] Regarding market entry, Nissan from Japan started producing and selling electric vehicle earlier than Tesla, with its Nissan Leaf introduced in 2010. While Tesla designed its Model S (introduced in 2012) based on an entirely new, battery-optimized platform, this is also true for Nissan's Leaf and the General Motors Chevrolet Bolt / Opel Ampera-e (2017). However, these vehicles did not enjoy Tesla's market success and did not influence the evolution of the BEV market. At the same time, although BYD also introduced its first BEV in 2010 (e6), it did not have a fully electric platform.

[30] Nissan Leaf (2010): 73 miles and Chevrolet Bolt (2017): 238 miles, compared with 265 miles for the Model S in 2012 already (Thomas & Maine, 2019).

EV. Table 8 shows, for a selection of vehicle manufacturers, the introduction year of their first BEV with a fully electric vehicle platform.

Table 8: Introduction year of the first electric vehicle with a fully electric platform of a selection of vehicle manufacturers.[31]

Manufacturer	Year	First BEV with a fully electric platform
Nissan	2010	Nissan Leaf
Tesla	2012	Model S
Chevrolet	2017	Chevrolet Bolt, using GM BEV2 platform
Volkswagen	2019	Volkswagen ID.3, using the MEB platform
Ford	2020	Mustang Mach-E, using the GE1 platform
BYD	2021	Ocean-X, using the e-platform 3.0
Hyundai/Kia	2021	Ioniq 5, using the E-GMP platform
Mercedes	2021	EQS, using the EVA platform
Renault/Nissan/ Mitsubishi	2022	Nissan Ariya, using the CMF-EV platform
Volvo	2022	Volvo XC40, using the CMA platform
Rivian	2022	R1T truck, Skateboard Platform
Toyota	2023	e-TNGA platform
BMW	2025	Neue Klasse platform

A new role arising from the introduction of BEV is the E-Mobility Service Providers (eMSP). An eMSP provides users with access to the charging network and arranges billing for their use (Klapwijk & Driessen, 2016). With Original Equipment Manufacturers (OEMs) gradually adopting a fully electric platform and the move towards Mobility as a Service (MaaS), the integration of OEMs and eMSPs is expected in the future. It is anticipated that eMSP integration will allow users to 'share' electric vehicles and have a seamless user experience in the vehicle charging process. Integration would also facilitate user access to charge point data, which is currently limited. Tesla does offer its users information on its proprietary Charge Point (CP) (Tesla, 2021), providing additional positive externalities. In fact, as the eMSP provider for its vehicles, Tesla could benefit more directly from the BEV business model's network externalities. Thus, it is no surprise that other firms have taken on different roles, such as VW, which is now also involved in eMSP integration and management (Figure 2).

In terms of interoperability, all the relevant regions of the world have developed a whole range of interoperability standards. These include standards for the charging connector, e.g., the IEC 62196 standard, which defines three connection types (IEC, 2014), and the CHAdeMO connector (CHAdeMO, 2021,c; TU Delft, n.d.), as well as standards for V2G Communication, such as ISO 15118 for bidirectional charging. Other standards already facilitate roaming services for the charging infrastructure, including CP locations and rates. In Europe, existing roaming protocols include the Open Clearing House Protocol (OCHP), the Open Interchange Protocol (OICP), the eMobility Interoperation Protocol (eMIP) and the Open Charge Point Interface (OCPI) (Klapwijk & Driessen, 2016; van der Kam & Bekkers, 2022).

Around 2014, after a long period of vertical integration and proprietary technologies, Tesla moved towards open standards for interoperability, sometimes prompted by legal requirements. In accordance with interoperability requirements set out in Directive 2014/94/EU, Tesla now uses CCS Type 2 connectors in its EU vehicles (European Parliament, 2014). But, in their own

[31] Own compilation based on data from Duffy (2021), Hao et al. (2023) and BYD (2021).

terms, Tesla decided to make its US-made vehicles compatible with the open CHAdeMO charging standard by using an adapter (Field, 2019). In November 2021, Tesla announced that non-Tesla EVs could now also use Tesla's supercharger network (Tesla, 2021). Tesla later developed and introduced a new proprietary charging plug standard (NACS) based on the ISO 15118 communication standard. This would allow all EVs in the US to access Tesla's supercharger network (Tesla, 2024). Tesla's knowledge-appropriation strategy underwent various stages. Initially building a significant patent portfolio, Tesla made its patented battery and charging technology freely available to others in 2015 and again in 2022 (Tesla, 2014; Chen et al., 2019; Moritz et al., 2015; Tesla, 2024). Criticised by some as a publicity stunt, this can also be seen as an enabler of technological diffusion and as strengthening the overall development of the BEV market. As shown in Figure 3 (Section 6.1), the BEV market has grown from 0.3 million in 2013 to 12.1 million in 2023 (IEA, 2024). By 2024, more than 20% of new vehicle sales worldwide were electric vehicles, and around half of those are BEVs (IEA, 2025). However, by 2024, Tesla still held the largest share of the BEV market (16.5%), with BYD in second place (16.3%) (Statista, 2025). Moreover, Tesla's revenue went from 6.1 billion dollars in 2015 to 41.8 billion dollars in 2022 (Statista, 2023).

Appendix B: Game Consoles

The second case study is Home Video Game Consoles, which people have been using to play games on their TV or monitor since around 1976, when the 'first generation' was introduced. This represents an interesting situation involving multiple ecosystems that, although parallel, are largely incompatible with each other. Each ecosystem also has its own network externalities. The market is dynamic and typically an unstable oligopoly.

B1 Scope for interoperability

Again, this is a case in which interoperability is critical to making the market possible. In this specific setting, interoperability can be (1) in the form of APIs and software libraries, (2) technical specifications for hardware elements, optical storage on a CD or DVD, and (3) telecommunications in the case of online gaming services. End-users' high expectations for new games mean that all the actors are working at the frontiers of what is possible, yet also require compatibility. As we will discuss in more detail, there are no open standards at the most critical points in the value chain, only proprietary standards closely controlled by the platform owner. Network effects are thus also vertically managed. In a game console, network effects are present in various ways: through the availability of (high-quality) games, the number of other users with which the game can be played, complementary hardware such as controllers and VR glasses, etc.

B2 Interoperability and market dominance

Video game consoles entered the market in the late 1970s as independent products with their own ecosystems. Both hardware functionality and software compatibility were designed and managed in-house. As such, there were no open standards specifying the technical or interoperability requirements between the most critical points in the value chain. Instead, these ecosystems were enabled by proprietary standards closely controlled by the platform owner. It was only after the market had further developed that firms moved away from a fully vertically integrated value chain, allowing some vertical specialisation through contracts with game developers.

The market for video game consoles, as we now know it, has evolved from consoles with single incorporated games to ones with interchangeable cartridges, allowing multiple games to be played on a single console. The Fairchild Channel F was the first console with a programmable and interchangeable cartridge system (Bogost & Montfort, 2007). Subsequently, the success of game consoles (hardware) was heavily based on the availability of sufficient and attractive game titles (software). Game console developers, who had thus far maintained a high level of vertical integration with their components, envisioned that game software would be developed in-house. However, it soon became evident that expanding their installed base required third-party game development. Initially, power relations were highly skewed in favour of the game console manufacturers, who through restrictive licensing and exclusivity agreements made sure they got most of the revenue from games, unlike game developers who bore the risks (Daidj & Thierry, 2009; Schilling, 2003; Lee, 2013; Hagiu & Spulber, 2013; Rochet & Tirole, 2003; Gallagher, 2012). However, the result of an antitrust investigation in 1992 (Atari Games Corp vs. Nintendo of America, Inc.) was a turning point that led to forced exclusivity contracts becoming less common in the industry (Lee, 2013). Exclusive titles are now secured through favourable contract terms with third-party developers (Lee, 2013). However, it is important to note that strong licensing agreements were necessary in the first generations to subsidise hardware sales and enable the sale of consoles at a loss (Schilling, 2003). Companies such as 3DO, which failed to find a balance between licensing revenues and production costs, failed (Schilling, 2003).

Game development is a complex process, as interdependencies must be considered among operating systems, game engines, and platform architectures (Laakso et al., 2014; Daidj & Thierry, 2009). Because each platform has its own ecosystem, interdependencies and individual requirements differ across platforms. Complexity and learning costs made it difficult to port games to different game consoles (multi-homing). Estimates put the cost of multihoming at hundreds of thousands or even millions of dollars (Lee, 2013). Aside from learning and production costs, the restrictive licensing agreements with game console manufacturers discouraged multi-homing. At this point, OEMs typically had both vertical integration via their hardware components and vertical specialisation through their agreements with game developers. Network externalities relating to the availability of game titles were also managed independently by each OEM. As the market for game consoles expanded, their manufacturers had to compete with incumbents and new entrants. Although the innovative strategy of the internal interface (Chen & Liu, 2005) was not uncommon, the dominance strategies varied, centred on two main points: selling consoles below production costs, and large network externalities through an extensive video game library (Schilling, 2003; Kirriemuir, 2000).[32] Across generations, the console with the most games released has almost always been the winner of its generation, with the notable exception of the Wii (Figure 5). Unlike the two runners-up, Xbox 360 and the PS3, the Wii differentiated itself through its innovative fun factor, resulting in higher sales. Interestingly, PS2, with the highest recorded number of games released, is not only the winner of its generation but also the best-selling platform, historically. As of 2024, almost 160 million units had been sold (VGChartz, 2022). Nintendo, the current leader of this generation, has sold about 138 million units of its Nintendo Switch and holds 63% of the market share (Statista, 2024). Sony and Microsoft hold 25% and 13% of the market, respectively (Statista, 2024). Game software availability is also important because of network externalities. Although after the antitrust investigation mentioned above, efforts to build a console's library included favourable agreements with third-party developers, it also included

[32] Nintendo's dominance in 1985 and Sega's in 1989 were mostly enabled through selling consoles for less than they cost to produce (Schilling, 2003). However, backward compatibility resulted in Sega having a much larger library than Nintendo, which is argued to be the main reason why Sega dominated the third generation (Schilling, 2003). Later, Sony's exclusivity agreements and ease of programming were essential factors that enabled it to build a large library and dominate the following generation (Schilling, 2003).

internal development and integration (Lee, 2013). The Sony PlayStation, for example, relies on a combined strategy of proprietary standards (OS, PSN services, PS controller) and vertical integration (first-party games and content distribution through the PlayStation store). Likewise, Microsoft moved towards a more vertically integrated strategy with its recent acquisition of ActiVision[33] (Spencer, 2022). Throughout its history, the game console market has been described as an unstable oligopoly (Daidj & Thierry, 2009). Many firms entered the market, yet only a few seriously competed for dominance, with different strategies and opportunities driving each one's success.

What appears to be a common trend is that firms unable to innovate in ways that benefit consumers or unable to gather a large enough installed base have failed to survive in the market. Marketing strategies, launch timing, and price (Gallagher, 2012) also play significant roles in determining a console's success. From the introduction of game consoles to the current generation, the number of competing consoles has dropped significantly (Table 7 in Section 6.2). Three factors have been identified that account for this drop. First, the degree of differentiation between the remaining consoles is becoming significantly lower. Note that this lack of differentiation can also help explain Microsoft's regained interest in managing the software section of the value chain. Second, the surviving consoles successfully demonstrated their technological and innovative superiority over those that have disappeared. Third, a shift towards shared network externalities (enabled by broadband connectivity) could potentially affect the number of competitors in the market.

Appendix C: Bank Card Payment Systems at Points of Sale (POS)

The third case study focuses on the financial sector and on electronic payment systems in stores, restaurants, etc., known as POS payments. This is a sector with strong network externalities; after all, the value of such services for a store is directly related to the number of clients able to make a payment. Security and government regulations also play an important role. Our case includes all methods/technologies of electronic POS payments (including swiping bank cards, chip and contactless cards), that can be either debit or credit cards but excluding non-electronic payments such as cash and cheques.

C1 Scope for interoperability

In payment services, interoperability is required at the following levels: (1) for technologies at bank card level, e.g., swipe, chip, contactless (Au & Kauff-man, 2008), (2) for security systems protecting bank-to-bank and bank-to-customer transactions (Leinonen, 2001), (3) between the financial institutions in order to transfer money between bank accounts (Leinonen, 2001) and (4) between banks - or acquirers - and card brands, for instance to register transactions and check whether payment limits have been reached (Au & Kauffman, 2008; de Luna et al., 2019).[34]

C2 Interoperability and market dominance

In payment services, interoperability is key to ensuring that a merchant can accept payments from all potential customers, regardless of the bank they have chosen, the type of (credit) card they have, or the country from which they are. Seamless compatibility from both the retailer and the consumer's perspective is considered necessary (Horvitz & White, 2000; Jarupunphol

[33] Activision is a U.S. game developer and publisher that owns the Call of Duty series.

[34] Standards for smart-card-based electronic payment systems and for the security of online payment systems are also being discussed in the industry (Asokan et al., 2000) but they are out of the scope of this paper since they do not apply at POS.

& Mitchell, 2003). This case study focuses on the payment systems used at POS. These include Stored Value Cards (SVC); cards with magnetic stripe (magstripe) technology; and cards with a chip, including cards that enable contactless payments through Radio-Frequency Identification (RFID) and Near-Field Communication (NFC) technologies (Table 9).

Payment cards used three different technologies: magstripe cards (based on ISO/IEC 7813) and contact or contactless smart cards, both based on EMV specifications (van den Breekel et al., 2016). Although they served the same purpose, magstripe cards were considered less secure, which is why, to reduce credit card fraud, they were replaced by smart cards in accordance with EMV specifications (van den Breekel et al., 2016; Jarupunphol and Mitchell, 2003). EMV specifications are based on two standards: ISO/IEC 7816 and ISO/IEC 14433, for contact and contactless cards, respectively (van den Breekel et al., 2016).

Table 9: Types of cards that can be used at POS.

Type	Defining characteristic	Guiding standards
SVC	Debit card with a specific amount of money stored in it.	
Magstripe cards	Credit or debit cards with a magnetic stripe	ISO/IEC 7813
Contact smart (chip) cards	Credit or debit cards with a chip enabling contact payments.	The EMV specifications, building on ISO/IEC 7816
Contactless smart (chip) cards	Credit or debit cards with a chip enabling contactless payments using NFC or RFID technologies.	The EMV specifications, building on ISO/IEC 14433.

An advantage of EMV specifications is that the same merchant terminal can be used for all different card brands (Jarupunphol & Mitchell, 2003) (Figure 6 in Section 6.3). However, EMV specifications were not immediately adopted worldwide (Gold, 2014). Europe was an early adopter, with all cards required to be compliant with EMV by 2010, and France became fully compliant with EMV in 2006 (Bouzefrane, 2009). This move was perhaps encouraged by the shift in liability that made the stores and shops at POS liable for fraudulent actions resulting from transactions in non-EMV supporting terminals (Bouzefrane, 2009). America and Australasia were late adopters of EMV-compliant cards and terminals (Gold, 2014). The delayed international adoption of EMV exposed the proclivity to fraud in international transactions with non-EMV-compliant countries (van den Breekel et al., 2016; Froud, 2016). Unfortunately, the same was true for cards with magstripe backward compatibility (van den Breekel et al., 2016; Gold, 2014). Therefore, stores stopped accepting stripe-based transactions with EMV-compliant cards to avoid liability for stripe-related fraud (Gold, 2014).

In Europe, Central and Eastern European (CEE) countries had the highest adoption levels, with over 80 per cent of the POS transactions being contactless payments by 2018. This became possible when Poland, with one of the top 10 Visa debit card issuer banks in Europe, migrated more than 6 million of its cards to contactless. Adoption was further boosted by supporting POS terminal installation and all stakeholders' approval of contactless cards (Visa, 2019). However, this was in sharp contrast to the adoption trends in the rest of Europe. Although NFC technology had been available since 2002 (Karjaluoto et al., 2020) and the first contactless payment trials were launched in 2007 (Pasquet et al., 2008), contactless cards were not immediately deployed. In the Netherlands, for example, they were not introduced until 2015, while by 2018, the market share of contactless payments was still low in countries such as Belgium and Germany (4 and 14 per cent respectively) (Karjaluoto et al., 2020). However, in Belgium, the share of contactless payments increased rapidly during the COVID pandemic, reaching 51% of total POS transactions by April 2021 (Febelfin., 2021). In Germany, on the other hand, privacy concerns and fear of accumulating debt are considered to be the reasons for the country's resistance to noncash payments (Vohra, 2023).

Contactless payments are now supported by a wide range of payment terminal types and brands, all of which support up to 10 payment methods (Wagenaar, 2026). These include traditional Visa and MasterCard credit cards, debit payments such as V-pay and Maestro, and new methods such as Apple Pay, G-Pay, and UnionPay (Wagenaar, 2026).

Although other payment methods have emerged in the realm of EMV-compliant cards, not all have been successful. This was the case of SVC. These cards were interesting since they could be used for small payments at POS, when bank cards were recommended for only larger transactions. In the Netherlands, for example, two SVCs were available: Chipper and Chipknip. However, in the second half of the 1990s, these two incompatible SVC systems were competing for retailers and customers, resulting in limited network value and uncertainty (De Vries & Hendrikse, 2001). Both systems failed completely and were ultimately withdrawn from the market.

Lastly, financial institutions also require standards to complete a payment transaction. SWIFT was originally the most widely accepted standard, but it failed to gain widespread international support (Leinonen, 2001). Its successor, the ISO 20022 standard, faced similar problems but became mandatory in the Single European Payment Area (SEPA) (Capgemini & BNP Paribas, 2018). Although the EU has moved towards integration, the lack of harmonisation at the international level has led countries like the US to have their banks deploy their own formats (Capgemini & BNP Paribas, 2018). Thus, it is anticipated that ISO 20022 will coexist with other standards for some time (Capgemini & BNP Paribas, 2018). It is difficult to determine from our literature review what drives the adoption of one payment method over another. Factors that can hinder adoption include diverse infrastructure requirements, fees, uncertainty about a method's success, or a variety of coexisting, incompatible payment methods. Thus, this market is caught between the effects of competition and compatibility. Due to network externalities, adoption depends on both retailer and consumer behaviour. On the retail side, adoption can be driven by a defensive strategy in which retailers fear that failing to adopt all methods could lead to business losses (Bounie et al., 2017). For consumers, adoption appears to be mainly related to socio-cultural, environmental, and regulatory factors, although the size of the network infrastructure may also drive adoption of technology (Guibourg, 2001). In this case, it relates to what is known as a 'pay everywhere guarantee'. Payment terminals that accept at least 10 different payment methods are a good example of this. Finally, from the perspective of card networks, security concerns seem to be the main drivers of developing and adopting a new technology.

Appendix D: Home Computers

This case focuses on the home computer market in the 1980s and 1990s, in particular on the MSX home computer, which represented an open-standards approach in this market. This case was specifically selected because it illustrates that, even in a market with strong network externalities, developing an open standard that ensures necessary interoperability across components does not guarantee its success.

D1 Scope for interoperability

It should come as no surprise that interoperability is a key prerequisite for a computer functioning in the first place. In the case of home computers, interoperability is required between (1) the computer OEM and the software used to drive the hardware, and (2) the hardware platform and the peripheral products. Without software compatibility, the computer's functionality was seriously diminished: people had to write their own code in BASIC, the programming language common to home computers at the time (Yamashita, 2020). Likewise, users were unable to connect storage devices such as floppy disks or data cassette recorders, or I/O devices such as joysticks, printers, keyboards, and mice. Before MSX, a very common form of differentiation in this market and a way to distribute high-performance software (especially games) was through hardware expansion cartridges that were slotted into the computer (Yamashita, 2020). MSX tried to address this by enabling hardware and software compatibility.

D2 Interoperability and market dominance

The market for home computers began in the 1980s, when microprocessors and other components made it feasible to leap from mainframes and develop computers for individual users (Robinson & Cargill, 1996). Unlike the mainframe, which was mainly aimed at industrial use, these computers could be used for business, entertainment, education, programming, and basic text writing (Yamashita, 2020). We distinguish between 'home computers'[35] not aimed at a professional customer base, which were relatively affordable and typically connected to a TV set; and Personal Computers (PCs), designed for business/office use in a personal environment, typically requiring a specific computer monitor, and considerably more expensive.[36] However, this distinction blurred towards the end of the period, and personal computers entered private homes.

Home computers were initially built as independent systems with their own proprietary standards (Robinson & Cargill, 1996). Although most computers used Microsoft's programming language (Yamashita, 2020), the operating systems developed by each manufacturer were unique to their specific computers and models. Each computer thus required a language-processing system tailored to its unique specifications (Wiltshire, 2020; Yamashita, 2020; Robinson & Cargill, 1996). As the specifications in each computer's Operating System (OS) differed from those of its predecessors and successors, each machine required its own programs, or the programs' software, to be ported from one language to another (Yamashita, 2020; Robinson & Cargill, 1996). So, despite the network effects clearly requiring compatibility, most home computers were entirely incompatible with each other (Figure 8). As mentioned above, each had to run different software programs. And, unlike current computers, they did not support compatible peripheral hardware either. The very popular Commodore 64 computer only worked with printers and storage devices specifically designed for it. A Sinclair ZX Spectrum, another successful home computer, only worked with its own specifically customised peripheral devices. Even the data storage formats (on tape cassettes or floppy disks) were incompatible. Overall, this severely constrained users' decisions, as they faced the serious risk of buying a computer that would soon be obsolete, orphaned, or never take off in the first place (Yamashita, 2020). The very popular Commodore 64 and Sinclair ZX Spectrum, however, benefited from strong network externalities (including a wide availability of software, especially games), which reinforced their commercial success.

Against this background, companies sought an open platform that would enable the use of third-party software (as well as hardware). In the early 1980s, initiatives tried to develop a standard for home computers that would offer complete compatibility between all (relevant) hardware and software characteristics regardless of the manufacturer (Yamashita, 2020; Duesenberry,

[35] Stefan Walgenbach of the German Home Computer Museum describes home computers as having at least two of the following characteristics: (1) ability to hook up to a TV (UHF, VHF or SCART), (2) a CPU and keyboard in a single case, (3) a ROM-based Operating System or programming language, (4) an external power supply, (5) with a non-typewriter keyboard (e.g. mini-keyboard or rubber keys) (Walgenbach, 2022).

[36] Source: interview with Mr. S. Walgenbach of the Herman Home Computers Museum, June 22, 2022.

1985). The original developers, Microsoft and ASCII (Yamashita, 2020; Baron, 2010), acknowledging the difficulties of making specialised, expensive, and time-consuming software for each computer, created a computer standard enabling 100 per cent compatibility of application software (Yamashita, 2020; Methe et al., 1998). The standard was called MSX[37] and it was designed to enable the compatibility of different manufacturers' hardware and software (Yamashita, 2020). The MSX computer's slot-bus architecture, which allowed the insertion of cartridges, gave manufacturers the opportunity and flexibility to differentiate their products: Yamaha, for example, incorporated music synthesiser hardware, while Panasonic MSX included word-processing software (Yamashita, 2020; Camper, 2009). Like the much more expensive IBM PC for office use (Singh, 2011), the system was designed primarily around off-the-shelf components, in the case of the MSX, the Zilog Z80 CPU (Camper, 2009; Baron, 2010).

MSX was announced in 1983 (Baron, 2010) and adopted by many companies, including Panasonic, Philips, Spectravideo International, Telematica, Gradiente, Sharp, Goldstar (now known as LG), Daewoo, Samsung, Casio, Canon, Kyocera, Sanyo, General, Sony, Toshiba, Yamaha, NEC, JVC, Pioneer, Hitachi, Fujitsu, Matsushita, and Mitsubishi (Methe et al., 1998; Yamashita, 2020). Although this includes many large consumer electronics companies, note that none of them was a major player in this home computer market (and we do not see Commodore, Sinclair, or Atari among the MSX adopters), and that there is a dominance of Japanese players keen to enter the home computer market.[38] Released the same year as the Nintendo game console, MSX was also a platform for which major Japanese game studios such as Konami and Hudson Soft wrote their games (Camper, 2009). Game developers were attracted to MSX due to its high level of standardisation, which later strongly influenced Microsoft's initial strategy for the Xbox[39] design (Camper, 2009). Access to DirectX specifications is restricted by an NDA (Microsoft, n.d.). The computer market was mainly software-driven (Bride, 2011; Gallagher, 2012). The first personal computer[40] on the market is arguably the Apple II[41] introduced in 1977, which was a success in great part thanks to the availability of a spreadsheet programme VisiCalc[42] (Bride, 2011; Den Hartigh et al., 2016). The IBM personal computer, introduced in 1981, also benefited from the wide availability of useful software. In Japan, NEC's PC-8000 was the representative PC of the time, with its text-entry functions notably supporting Kanji characters (Yamashita, 2020). However, these computers were intended for the high-end market and, as such, had a higher price tag than MSX (Den Hartigh et al., 2016; Yamashita, 2020; Baron, 2010; Methe et al., 1998). Upon release, MSX

[37] The acronym has no official meaning, although (Duesenberry, 1985) and others suggest that it refers to Microsoft Extended. Kazuhiko Nishi suggested that the name came from Machine Software Exchangeability (2001).

[38] The Japanese had been looking to enter the home computer market for some time, but moreover required computers enabling Japanese language support (Yamashita, 2020).

[39] Although Microsoft finally opted for a more centralised approach, it also made sure to facilitate game development from third parties by keeping the same APIs as in the PCs. Furthermore, in 2000, Microsoft used the Windows OS to develop the XBox, making it easy for those already creating computer games to develop games for it. Then, in 2006, it used the DirectX Application Programming Interface (API) on the XBox360 (Daidj & Thierry, 2009).

[40] Please note how we distinguish between home computers and personal computers in the paper, as explained at the beginning of this section.

[41] Although IBM PC eventually won the industry battle, up to the 1980s it seemed Apple was best positioned to win (Den Hartigh et al., 2016). Fast forward to the future, we see that Apple's central control approach has been more profitable (Den Hartigh et al., 2016).

[42] VisiCalc was a business tool allowing companies to check their balance sheets and perform balance calculations with relative ease (Den Hartigh et al., 2016).

computers had a price tag of 50,000 yen (around $390), almost a sixth of the price of the NEC's PC-9801, priced at 298,000 yen ($2317) (Yamashita, 2020; Baron, 2010; Methe et al., 1998). Although it was a low-priced product, MSX had sufficient functions and adequate performance, not to mention that it could use a standard television rather than requiring its own dedicated display (Yamashita, 2020). Figure 9 shows the introduction year for the market and compares the introductory prices of certain home and personal computers.

Marked by a rapid technological pace, the market for home computers has seen many manufacturers and models, some more successful and long-lasting than others. The most successful home computers were the Commodore 64 of 1982, with around 17 million units sold over a 12-year period (Fenlon, 2012) and the ZX Spectrum from 1982, with over 5 million units sold over a 10-year period (Fenlon, 2012).[43] For MSX computers, around 5 million units were sold worldwide (Camper, 2009), significantly less than the Commodore 64. Notably, most of these units were sold in Japan (Camper, 2009; Yamashita, 2020), with continental Europe, South Korea, Argentina, and Brazil as other important markets (Yamashita, 2020).

The lack of sales in the United States, a key global market for home computers, stems from the fact that, despite Microsoft's involvement, few MSX-based machines were released there (Camper, 2009; Baron, 2010; Wiltshire, 2020). Manufacturers probably feared the intensely competitive US market, and what was called the price war[44] started by Commodore (Yamashita, 2020; Perry & Wallich, 1985; Wiltshire, 2020). Finally, the IBM PC, released in the United States in 1981, proved extremely successful and had one thing in common with MSX: it provided an open architecture that enabled third parties to develop software for it and expand its network externalities (Bride, 2011). However, a major difference is that the IBM PC was based on a proprietary standard developed by IBM and its supplier, Microsoft, while MSX was an open standard developed by stakeholders. Moreover, not long after the introduction of MSX, more expensive (Fenlon, 2012), but notably more capable 16/32-bit computers like the Apple Macintosh (1984), Atari ST (1985; where ST stood for 'Sixteen Thirty'), and Commodore Amiga (1985) hit the higher price segment of home computers (Yamashita, 2020). The IBM PC, originally targeted at the office market, gradually became a more relevant choice for home use as well. In the gaming area, MSX also failed to become the leading platform, mainly due to its limited performance as a dual machine (console-computer) compared to dedicated technologies (Camper, 2009; Methe et al., 1998).

[43] Considering personal computers, the most successful ones in this era were the Apple II (1977, around 1 million units sold) (Fenlon, 2012) and the IBM PC (1981, around 2 million units sold by 1984) (Reimer, 2005).

[44] The 1982 Commodore 64, including processor, graphics, sound chips and 64 kb of memory, was introduced for US$595 and its price continued to drop to even $149 in 1985 (Perry & Wallich, 1985).

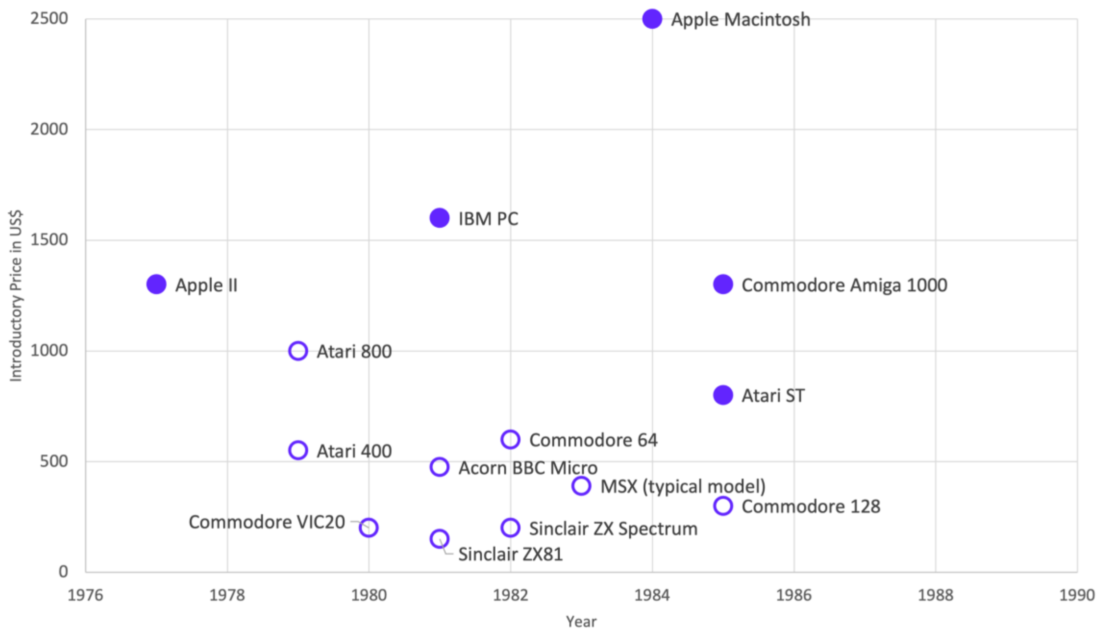

Figure 9: Selected computers' market introduction (year) and introductory price ($USD). Home computers are represented with an outlined marker, while personal computers are represented with a filled, purple marker. Various compiled sources.

Production of MSX computers (first generation) ceased in 1995 (Yamashita, 2020), while IBM PCs and their clones gained popularity, eventually making IBM the market leader, including in the home computer segment (Den Hartigh et al., 2016). MSX did not disappear immediately. It was still very popular in Japan, and there were several new generations. MSX2 (1985), MSX2+ (1988), MSX TurboR (1990), but with each new generation, the number of companies adopting it decreased along with sales (Methe et al., 1998). Despite Microsoft's involvement in MSX, the lack of other key market players' involvement adds to the reasons for MSX's short lifespan.

MSX as an open standard failed, but this did not stop other (vertically integrated) firms from entering the home computer market. Other notable home computers launched after MSX include the Amstrad/Schneider CPC of 1984, the Apple IIGS of 1986, the Acorn Archimedes of 1987 and the Commodore Amiga 500 Plus of 1991 (Wiltshire, 2020). The latter being the second-most-sold home computer after the Commodore 64, with around 6 million units sold (McFadden, 2019). Furthermore, while MSX ultimately disappeared from the market, other firms that had initially been involved in the home computer market eventually moved into the personal computer market, including Toshiba, one of the initial parties to MSX.