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ORIGINAL ARTICLE

Measuring network effects of digital industrial platforms: towards a balanced platform performance management

Fabian Schüler[1] · Dimitri Petrik[2]

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Abstract

Firms increasingly establish digital industrial platforms to cope with the adaption of the industrial internet of things (IIoT) paradigm. The tremendous success of digital platforms in many platform-mediated industries can be traced back to the ignition of network externalities. However, the impact of network externalities is still under discussion in the IIoT domain, and their measurement remains a challenge for platform companies. This paper outlines how network effects were measured in the existing research, deriving three dimensions of network effects for IIoT: (1) ecosystem utility, (2) complementarity, and (3) compatibility. This conceptualization is further used in an empirical study with practitioners from digital industrial platform organizations to enable performance measurement of network effects in IIoT by developing 20 key performance indicators (KPIs). Based on the empirical study results, this paper proposes a framework for balanced platform management. Utilizing the goals of a balanced scorecard, the framework emphasizes the trade-off between the contradicting perspectives on costly network effect simulation and platform earnings that platform managers need to balance. The KPI portfolio can support platform managers in implementing the framework.

Keywords Industrial internet of things · Digital industrial platforms · Network effects · Performance measurement · KPIs · Balanced scorecard

✉ Dimitri Petrik
dimitri.petrik@bwi.uni-stuttgart.de
https://www.linkedin.com/in/dimitripetrik/

Fabian Schüler
schuelerfabian@gmail.com
https://www.linkedin.com/in/dr-fabian-sch%C3%BCler-599646163/

1 IPRI - International Performance Research Institute gGmbH, Augustenstr. 19, 73760 Ostfildern, Germany

2 Dept. VIII: Information Systems II, University of Stuttgart, Keplerstr. 17, 70174 Stuttgart, Germany

1 Introduction

Recent technological advancements in cloud, analytics, and connectivity technologies offer tremendous potential for efficiency gains and new business models, including the organization of industrial production (Legner et al. 2017; Sandberg et al. 2020). The increasing integration of information technologies in industrial processes and the associated equipment, known as the industrial internet of things (IIoT) paradigm, enables companies to solve more complex customer problems by combining physical and digital components and creating value-added insights from advanced analytics (Boyes et al. 2018; Beverungen et al. 2020). Nevertheless, IIoT architectures usually require digital industrial platforms as a scalable and interoperable development infrastructure for connected industrial assets and digital services to extract added value from the inter-organizational use of data. Utilizing the digital software platform concept, broadly used in the existing information system (IS) research, digital industrial platforms are modularly extensible codebases of software systems equipped with interfaces openly accessible for third-party firms to utilize the platform core (Tiwana et al. 2010; Hein et al. 2020). Accordingly, from the technical perspective, digital industrial platforms act as middleware systems, fitting the infrastructural needs for integrating industrial devices and developing complementary digital services (Yoo et al. 2010; Wortmann and Flüchter 2015; Mineraud et al. 2016; Pauli et al. 2021).

Organizations with digital platforms in their portfolios, like Apple, Google, Amazon, and Microsoft, rank among the world's most valuable firms (Gawer 2020; Parker et al. 2017). However, a mere technical view is insufficient to understand the mechanisms that make the platform providers so valuable. This is because platforms simultaneously facilitate transactions between different market sides (i.e., demand and supply) and act as innovation engines for the development and provision of platform-based applications or services (i.e., by reducing development efforts), forming ecosystems of autonomous actors (Gawer 2014; Cennamo 2019; Hein et al. 2020). Both ways to leverage value based on digital platforms are determined by the network effects as an important underlying economic principle (Thomas et al. 2014; McIntyre and Srinivasan 2017; Song et al. 2018; Gawer 2020). In particular, complements create positive network effects for the platform provider, increasing the platform value for the ecosystem actors. Since network effects are recognized to create bandwagon effects once a critical mass has been reached, they are considered an intangible factor in inter-platform rivalry (Stummer et al. 2018; Cennamo 2019). Consequently, the knowledge of creating and nurturing network effects for all ecosystem actors becomes a critical capability for platform-providing organizations to embrace (Tiwana 2014; Haki et al. 2022).

While strong network effects have led to dominant market positions of individual firms in platform-mediated business-to-consumer (B2C) markets (Cusumano et al. 2019), this effect has hardly been observed so far for the highly fragmented and competitive IIoT domain (Lueth 2019). Despite the rich scientific foundation on the network effect theory, existing research recognizes that network effects' impact and structure vary across domains (Basu et al. 2003; Afuah 2013). Based on the examples of database management systems and server software, prior research even highlights how network effects can manifest differently even within a comparative context (Gandal 1995; Gallaugher and Wang 2002). Hence, conceptual work based on game theoretic models (Farrell and Saloner 1986; Chen and Guo 2022) lays important foundations for platform management but does not consider the specifics of the business-to-business (B2B) domains, thereby oversimplifying the platform management practice and neglecting the complexity of utilizing network effects for digital industrial platform providers (Basu et al. 2003; Pauli et al. 2021). As a result, the impact of network effects in IIoT is still debated based on different research findings (Menon et al. 2019; Pauli et al. 2021; Mosch et al. 2023).

These shortcomings indicate an issue for digital industrial platform providers, hinting a lack of guidance for the practice to establish platform ecosystems and control the evolvement of industrial platform ecosystems in the prior research (McIntyre and Srinivasan 2017; Pauli et al. 2021; Hein et al. 2019; Schreieck et al. 2022). The insufficient exploitation of network effects is even reflected empirically by the fragmented and thus relatively immature digital industrial platform market (Pauli et al. 2021; Arnold et al. 2022). This is likely to affect IIoT domain characterized by intensive competition between industrial incumbents (e.g., Siemens, Schneider Electric, or Hitachi) and platform natives for complementary innovation (Cennamo 2019), putting incumbents in a difficult position. Mastering the creation and maintenance of network effects is a challenge for industrial incumbents in contrast to their previous pipeline businesses (McGrath 2020; Marheine et al. 2021). Yet, they have to specialize in order to differentiate their platform from platform natives like Microsoft or AWS, while the specialization on the platform architecture and application levels impedes the creation of network effects (Pauli et al. 2021; Mosch et al. 2023). Although platform literature formulates several strategies expected to stimulate network effects (Eisenmann 2006; Stummer et al. 2018; Rietveld and Schilling 2021), little is explored about how these strategies can be executed. While management typically requires performance measurement to execute strategies (Micheli and Gupreet 2021), the research on performance measurement for platform ecosystems is in an infant state (Floetgen et al. 2022). To support performance management in the platform context, it is necessary to be able to measure impactful economic logics as network effects. However, the existing empirical research on network effects largely misses the guidance on network effect measurement (Nair et al. 2004; McIntyre and Srinivasan 2017; Schüler and Petrik 2021), predominantly focusing on the different outcomes caused by network effects (such as implications for pricing or decisions on intellectual property sharing) in the respective domains (Basu et al. 2003; Gallaugher and Wang 2002; Niculescu et al. 2018).

The aforementioned gaps indicate a lack of integration between understanding and executing platform strategies, given that internalizing the external network effects is a central pillar of the platform competition dynamics (Gawer 2014; McIntyre and Srinivasan 2017). Therefore, further analysis of their operationalization bears a high practical relevance from the perspective of platform-providing firms. Although empirical results are already available for measuring network effects as a

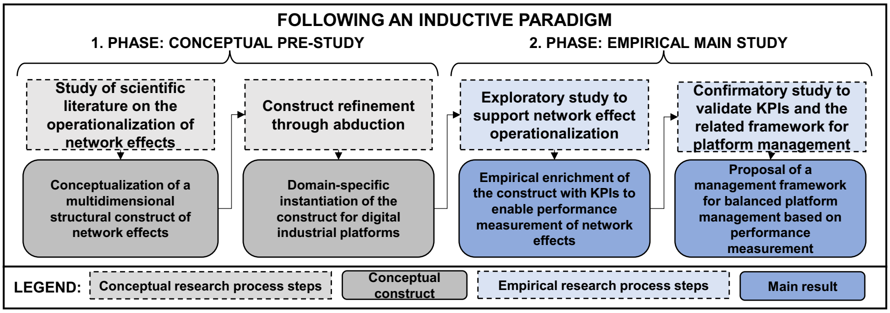


Fig. 1 High-level overview of the study

key value driver of platform-based business models, they are given little consideration in the operational and strategic management of platform-based business models due to the high level of abstraction of the studies (McIntyre et al. 2020; Nair et al. 2004; Wallbach et al. 2019). Consequently, we argue that the operationalization of network effects requires further research to support platform providers in IIoT in measuring network effects to steer them in a meaningful way. Inspired by the structural analysis of network effects by Afuah (2013), the research goal of this study is to decompose network effects into operationalizable dimensions, instantiate them in the IIoT context and propose key performance indicators (KPIs), enabling their measurement,and supporting balanced platform performance management (Chen et al. 2021). Therefore, our research focuses on the following research question: *Which key performance indicators (KPIs) should digital industrial platform providers analyze to measure the network effects*?

We conduct a two-phase research study following the inductive paradigm. During the conceptual pre-study, we explore the structure of network effects by studying the literature on the previously discovered approaches of operationalizing network effects. Subsequently, we conceptualize network effects as a multidimensional construct and apply abduction to instantiate the construct in light of the domain-specific moderators of IIoT. During the second phase, we perform a qualitative-empirical study with experts from the practice to enrich the construct with meaningful KPIs, and enable the performance measurement of network effects. Based on that, we perform abductive reasoning to propose a framework for balanced management of digital platforms based on performance measurement, whose implementation is supported by the previously identified KPIs. Figure 1 illustrates a high-level overview of the study:

Answering the calls from McIntyre and Subramaniam (2009) and McIntyre and Srinivasan (2017) for a detailed analysis of possibilities to measure network effects, the study makes three main contributions. First, our study is one of the few that extends the nascent body of knowledge on platform performance management (Floetgen et al. 2022), offering empirically validated KPIs to measure network effects and their influencing factors. Second, due to the chosen empirical setting, the results support the performance measurement of network effects for digital industrial platforms as a specific platform type that has not been exploited sufficiently in practice to generate and capture value from network effects, building an explicitly defined research avenue in the industrial use of platforms (Pauli et al. 2021). Third, we empirically derive a platform management framework by classifying existing KPIs according to their relevance, creating an artifact of practical use for platform providers to steer network effects and balance the trade-off between platform earnings and network effect stimulation (Chen et al. 2021). Therefore, our study goes beyond the plain understanding of network effects towards the measurement to guide targeted decisions in platform management, closing the gap between theory and practice by linking the theory of network effects with the KPIs-based operationalization. In doing so, the results support the practical implementation of network effect measurement by platform organizations.

The remaining paper is organized as follows. Section 2 aims to explain the context of our empirical study, introducing digital industrial platforms. Section 3 reports how network effects are measured in the existing literature to conceptualize a multidimensional and instantiated view on network effects for digital industrial platforms. Section 4 documents the applied empirical research design. Section 5 presents the empirical results on measuring network effects, reported by platform providers in IIoT, and the outlined framework for balanced platform management. In Sect. 6, we discuss the implications for practice and theory, ending the paper with a critical reflection and a conclusion for future research.

2 Digital industrial platforms and network effects

This section introduces digital industrial platforms and explains how the theory of network effects applies to this specific platform type, providing the foundation for an operationalizable network effects concept.

The concept of digital industrial platforms integrates both aforementioned value facilitation mechanisms of platforms. Therefore, digital industrial platforms simultaneously act as a technological infrastructure for development and an intermediary, organizing value co-creation in industrial domains (Thomas et al. 2014; Pauli et al. 2020, 2021; Mosch et al. 2023). On the one hand, digital industrial platforms allow data integration from information technology (IT) and operational technology (OT) to increase the efficiency of operational processes and foster the development and provision of digital industrial services, encapsulated as platform-based complements (Mineraud et al. 2016; Marheine et al. 2021; Pauli et al. 2021). On the other hand, digital industrial platforms with a transaction focus (i.e., industrial marketplaces) connect manufacturing firms (i.e., along the supply chain) to optimize supply and demand and manage distributed production, enabling new production paradigms (Müller et al. 2020; Friedrich et al. 2022; Mosch et al. 2023). Real-world manifestations indicate that many of these platforms evolve into hybrids (Cusumano et al. 2019).

Yet, digital industrial platforms differ significantly from their counterparts in the predominantly researched business-to-consumer (B2C) application domains. Prior research on platform ecosystems has mainly focused on B2C domains such as mobile and video game platforms (Ghazawneh and Henfridsson 2013; Cennamo and

Santalo 2013), with only few studies in enterprise domains (Ceccagnoli et al. 2012; Sarker et al. 2012). However, the rare empirical studies on digital industrial platforms show that transferring assumptions about platforms from B2C leads to incorrect management decisions and threatens successful platform establishment (Marheine and Petrik 2021; Pauli et al. 2021). Thus, the distinctive attributes of digital industrial platforms are presented in the following.

First, the prevailing lack of interoperability of industrial assets is one of the key specifics of the IIoT domain, extending the platform purpose to form inter-organizational integration middleware systems (Boyes et al. 2018; Pauli et al. 2021). Therefore, digital industrial platforms are considerably less standardized compared to the innovation platforms in B2C domains (i.e., mobile operating systems). To increase the interoperability between industrial assets and enterprise software across organizations, digital industrial platforms vary greatly in their architectural designs. Hence, such platforms range between cloud- or edge-based architecture, supporting different data structures, and application deployment approaches to meet individual industrial requirements (Arnold et al. 2022). In this context, the interoperability mechanisms (Noura et al. 2019; Pauli et al. 2021; Hodapp and Hanelt 2022) are also more diverse and individualized than the dominant duopoly of platform architectures for mobile OS. A second difference lies in the increased individualization at the application level (Pauli et al. 2021; Stoiber and Schönig 2022). Tailoring industrial applications to the individual requirements of the industrial end customers requires dyadic-level interactions during the complement creation, contrasting the standardized arm-length development of complements predominantly discussed in the literature (Marheine et al. 2021). Digital industrial platform providers, complementors, and industrial end customers help each other to cope with the inherent complexity of the digital industrial architectures (e.g., IoT stack) by mutually closing technological gaps and handling data critical to competition on the platform (Yoo et al. 2010; Wortmann and Flüchter 2015; Hein et al. 2019, 2020; Pauli et al. 2021). The co-creation is characterized by complex and less standardized (i.e., dyadic) collaborations between multiple organizations (e.g., along the value chain) (Petrik and Herzwurm 2020; Kenney et al. 2019; Pauli et al. 2021), so the scope and the means of platform governance significantly differ from B2C (Marheine and Petrik 2021).

The diversity of architectures, the individuality of applications, and the heterogeneity of players in the IIoT moderate the growth of digital industrial platforms (Wee et al. 2015), challenging platform establishment and value capture from network effects (Kammerlander et al. 2018; Marheine et al. 2021). Known platform-based IIoT ecosystems are smaller and grow slower than the research from other platformized domains suggests. On the contrary, the presented differences led to a dynamic inter-platform rivalry in the market for digital industrial platforms, compared with the B2C domains where the winner-takes-all logic prevailed (Lueth 2019; Arnold et al. 2022; Kwak et al. 2018; Friedrich et al. 2022). Accordingly, the dynamic inter-platform rivalry in IIoT turns the facilitation of network effects into a meaningful platform provider objective due to their recognized effect of intangible competitive advantage (Evans and Basole 2016; Hein et al. 2019, 2020; Cennamo 2019). After all, platform providers are in the position to facilitate network effects, drawing on the interdependency of network effects on platform-using firms and complements (Ghazawneh and Henfridsson 2013; Song et al. 2018; Pauli et al. 2021). Based on their openness for third-parties, the economies of scale and scope are often assumed with the network effects acting as determinants for leveraging the value facilitation mechanisms of digital platforms used in the industrial context (McIntyre and Srinivasan 2017; Kenney et al. 2019; Pauli et al. 2021). Platform openness attracts complementors to increase value for industrial end customers, indicating the presence of indirect network effects in IIoT (Menon et al. 2019). Existing research finds a negative correlation between network effects and the platform providers' vertical efforts, implying that platform providers must increase their vertical efforts when network effects are weakly developed (Parker et al. 2017). Thus, given appropriate ecosystem management, the general logic of the platform user attraction results in platform externalities, leading to indirect network effects (McIntyre and Srinivasan 2017; Jacobides et al. 2018). Therefore, most digital industrial platforms deploy governance mechanisms to facilitate network effects (Stummer et al. 2018; Chu and Manchanda 2016; Pauli et al. 2021). However, it is also assumed that the individualization of industrial complements decreases their value for other industrial customers, limiting the direct network effects among the demand side actors (Pauli et al. 2021). Thus, network effects created in the context of digital industrial platforms are likely to be asymmetrical.

Network effects also apply for digital industrial platforms with a transaction focus. The use of such platforms depends on the number of contracting platform users and manufacturing suppliers offering their production capacities via the platform to strive for cost or quality leadership (Rong et al. 2018a; Kwak et al. 2018; Pauli et al. 2021). However, compared to B2C marketplaces, a holistic optimization of the production workload requires significantly deeper and more complex technical integration (Pauli et al. 2021; Arnold et al. 2022) to coordinate the integration of individual value-creation steps in a distributed production network (Rong et al. 2018a; Kwak et al. 2018).

In summary, while the presence of network effects in digital industrial platforms is indisputable, they cascade more slowly and their generation is less obvious than discussed in the literature on other platform-mediated domains (Thomas et al. 2014; Marheine and Petrik 2021). Value creation mechanisms for industrial platform users are more complex compared to platforms used in B2C (Pauli et al. 2020, 2021), and the exploitation of strong network effects in the IIoT domain is still a substantial problem that could be addressed with a better understanding of the network effects structure. Despite the recent recognition of network effects as a significant ecosystem benefit in the context of IIoT (Cao and Thomas 2021), there is still little research (Tiwana 2014) on their operationalization, specifically considering the distinctive aspects of digital industrial platforms, which is essential for performance measurement and for monitoring the implementation of platform strategies (Floetgen et al. 2022; Micheli and Gupreet 2021). While Nair et al. (2004) conducted important work quantifying network effects, the authors isolated only one market side. Chu and Manchanda (2016) considered two market sides quantifying network effects in the context of consumer-to-consumer platforms. Therefore, IIoT domain instantiation helps adjust the detail level to quantify network effects as an object of interest and provide feasible recommendations on how research and practice can operationalize network effects in complex B2B setting.

3 Conceptualizing network effects for performance measurement

This section summarizes the main aspects of the network effect theory and synthesizes previous operationalization or decomposition approaches to conceptualize and instantiate network effects for digital industrial platforms.

3.1 State of research on the measurement of network effects

The theory of network externalities examines the increase in platform value by a new user, so the total benefit of network technology to a potential technology user is estimated by the term $V = a + b(N)$. Variable a represents the network-independent benefit a user experiences using the new technology. This occurs when a new technology is superior to the existing technology and increases the adaptation rate of the new technology (Farrell and Saloner 1986). The term $b(N)$ represents the added value derived from the network's users. Network effects arise when the benefit increases with each additional user, which applies to features of physical networks and technology, network standards or digital platforms (Kauffman et al. 2000; Katz and Shapiro 1994; Evans and Schmalensee 2016). The effects are also called consumption externalities (Katz and Shapiro 1985). Consumption externalities can be divided into direct and indirect network effects. In the platform context, positive direct network effects increase the value of a platform with additional users within the same user group (i.e., same market side), and positive indirect network effects increase the value of a platform with additional users from the other user groups (i.e., other market side) or platform-based content (Wallbach et al. 2019; Cennamo and Santalo 2013). As a distinguishing criterion, Gawer (2014) points out that direct network effects are predominantly generated by positive economies of scale, whereas positive economies of scope characterize indirect network effects. However, an oversupply can reduce the added value of a platform ecosystem, creating negative network effects (Wallbach et al. 2019). Generally, network effects rapidly transfer negative developments to the entire ecosystem, so digital platforms can also suffer a decline (Duan et al. 2009; Evans and Schmalensee 2016). Overall, if a platform provider sets up performance measurement by defining appropriate KPIs, an objective base for measuring network effects and evaluating the stimulation efforts within a platform strategy can be created (Tiwana 2014; Parmenter 2019).

Since the number of network users influences the network's value, delineating the network participants becomes essential. The central characteristic of the relevant network is whether the products of different network participants create synergies or can be used together. In the case of communication networks, the question of whether contacts from other providers or alternative technologies can also be reached with the service is decisive for the usable network size. If two companies' systems are interconnected or compatible, the total number of users forms the corresponding network. The same applies to digital industrial platforms, where complements are developed for specific hardware or run on a different hardware configuration. The relevant network in the second scenario again consists of all users of compatible hardware (Schüler 2022).

To identify the characteristics capable of coping with the complexity of digital industrial platforms and enabling performance measurement, we initially conducted a literature review aiming to perform a structural analysis of network effects. During the first search, we follow the recommendation of Webster and Watson (2002) to start with leading journals. Since network effects in the context of digital industrial platforms are an interdisciplinary topic, we have refrained from using the AIS Senior Scholars' Basket. Instead, academic journals in categories A+, A, and B according to VHB-JOURQUAL 3 ratings for the IS, strategic management, and general business administration disciplines were considered. This initial scoping review targeted high-impact literature reviews and research agendas on digital platforms to understand key research outcomes and applications. Overall, seven literature analyses and research agendas (see Table 1) were identified and screened for references to identify previous operationalizations of network effects. The backward search helped discover additional keywords for a subsequent database search and led to identifying the first sample of relevant papers.

The second search aimed to incorporate a diverse spectrum of relevant literature on the structure and operationalization of network effects. After testing different search string variations, we defined a search string combining the keyword "network effects" with the combination of keywords "quantification", "operationalization", "measurement", "structure", "KPI" and "metric". A combined string was used in seven scientific databases: Ebscohost, ScienceDirect, ACM, IEEE Explore, AISeL, SpringerLink, Taylor and Francis, and Wiley based on titles, keywords, and abstracts. Figure 2 presents an overview of the literature review approach and the screening steps complementing the first literature search.

The paper selection was guided by inclusion and exclusion criteria. Only peer-reviewed journal papers that conducted a structural analysis of network effects or provided information on the operationalization or measurement of network effects were included in the second search. Papers with other research objects only mentioning network effects or papers that created theoretical models to illustrate different organizational behaviors under network effects were excluded from the sample. Although empirical papers were preferred, conceptual papers and seminal such as the paper by Afuah (2013), were included in the final sample. Due to the lack of papers on network effects in the context of IIoT, no domain-specific boundaries on the paper inclusion were set, requiring a careful interpretation by the authors in consultation with external senior researchers.

The inclusion of the papers depended on the authors' interpretation of the paper results and their expertise on digital industrial platforms. Therefore, the synthesis followed an abductive research approach, which seemed the best solution to create a sample based on insights from outside the researched context or theoretical frame. For example, converters with standardized data and interfaces (Farrell and Saloner 1992), as well as payment methods on commerce platforms (Hinz et al. 2020), extensions or content (Song et al. 2018; Rong et al. 2018b) were interpreted

Table 1 Prior measurement approaches for network externalities

Literature reviews and research agendas from the first search	Search Nr	Relevant papers on network effects measurement	Network effects dimensions			
			Network size	Ecosystem utility	Comple-mentarity	Compat-ibility
Thomas et al. (2014) McIntyre and Srinivasan (2017) Jacobides et al. 2018 Schüler and Petrik (2021) Rietveld and Schilling (2021) Kapoor et al. (2021) Chen et al. (2021)	1	Farrell and Saloner (1992)				X
	1	Pae and Hyun (2002)	X			
	1	Nair et al. (2004)			X	
	1	Parker and Van Alstyne (2005)		X		
	1	Zhu et al. (2006)	X			
	1	Lai et al. (2007)	X			
	1	Lin and Bhattacherjee (2008)	X		X	
	1	Tanriverdi and Lee (2008)			X	
	2	Markovich and Moenius (2009)				X
	2	Pontiggia and Virili (2010)	X			
	2	Galbreth and Shor (2010)	X	X		
	1	Lin and Lu (2011)	X		X	
	1	Lin et al. (2011a, b)	X	X		
	2	Schief et al. (2012)			X	X
	2	Dey et al. (2012)	X			
	1	Zhao and Lu (2012)	X		X	
	1	Chiu et al. (2013)	X		X	X

Table 1 (continued)

Literature reviews and research agendas from the first search	Search Nr	Relevant papers on network effects measurement	Network effects dimensions			
			Network size	Ecosystem utility	Comple-mentarity	Compat-ibility
	1	Afuah (2013)		X		
	1	Kim et al. (2014)			X	
	1	Gao and Bai (2014)	X		X	
	2	Heinrich (2014)				X
	1	Zhou (2015)	X		X	
	2	Boudreau et al. (2015)				X
	1	Kang and Namkung (2016)	X		X	X
	1	Hsu and Lin (2016)	X		X	X
	1	Chu and Manchanda (2016)		X		
	2	Däs et al. (2017)		X		
	1	Zhang et al. (2017)	X		X	X
	1	Hong et al. (2017)	X		X	
	2	Thies et al. (2018)		X		
	2	Rong et al. (2018b)		X	X	X
	1	Song et al. (2018)		X	X	
	1	Mouakket and Sun (2019)	X		X	
	1	Cen and Li (2020)	X		X	X
	2	Hinz et al. (2020)		X	X	
	2	Tang et al. (2020)		X		
	2	Zhang and Yue (2020)			X	X
	–	Schüler (2022)		X	X	X
	2	Mullick et al. (2021)		X	X	

Table 1 (continued)

Literature reviews and research agendas from the first search	Search Nr	Relevant papers on network effects measurement	Network effects dimensions			
			Network size	Ecosystem utility	Comple-mentarity	Compat-ibility
	2	Gong et al. (2021)	X		X	X
	2	Li and Kettinger (2021)		X		
	2	Haurand (2022)		X		

as manifestations of distinctive network effect dimensions. During the coding procedure, we synthesized the research domains, methods, and the results, such as network effect characteristics and operationalization approaches. This helped to delineate the structure, coding four dimensions of the network effect operationalization. Table 1 sums up the literature sample of 41 selected papers from searches contributing knowledge on how the network effects were operationalized.[1] In addition, a dissertation on the object of interest was added to the sample. During the following analysis, we did not distinguish between the impact of network externalities and the focus on the platform or technology providers' ability to stimulate them.

The analysis of existing approaches reveals that many studies research social media due to the high user numbers and data availability. However, the findings from current research on social networking sites have hardly been adapted for enterprise software, particularly IIoT. Table 1 indicates that the focus on network size shows throughout all articles, regardless of their age. A comparison between the approaches in the literature shows differences between business IS and social media studies. While the latter operationalize direct network effects via the network size and the number of friends or contacts (e.g., peers) connected to the platform, studies in the context of business IS often focus on the horizontal and vertical trading partners of the company (Lai et al. 2007; Zhu et al. 2006). In order to standardize this structure, both approaches must be traced back to the core of the concept, which means that actors on the platform must bring an additional benefit to other actors. Since both dimensions describe the actors of the network, the main difference between the two operationalizations is that the utility of the ecosystem considers the sorting externalities, switching the focus on the composition of the ecosystem (Peitz 2006). This relationship goes back to Katz and Shapiro (1985) and the basic assumption that direct network effects result from direct (physical) interactions. In general, however, actor interactions are often limited to a small group of platform actors, while no interactions are conducted with a large part of the unknown mass of actors (Lee et al. 2006). This picture aligns with previous studies, which assume that there are hardly any direct network effects on digital industrial platforms (Schermuly et al. 2019; Pauli et al. 2021). The identified correlation can be attributed, among other things, to the heterogeneity of the use cases in the IIoT coupled with the high individuality and specificity of the solution approaches, which lead to an isolated development of the platform actors on one side and make interactions between them more difficult (Hanelt et al. 2020).

Prior research on operational IS has demonstrated a significant influence of network size: Lai et al. (2007) or Zhu et al. (2006) have often implicitly considered sorting externalities in operationalizing direct network effects. Research demonstrating the influence of total network size has mainly been conducted in the context of communication or social media platforms (Kang and Namkung 2016; Lin and Lu 2011). Still, four of the constructs discovered in the literature sample and related

[1] The literature sample was updated after the empirical study to support the discussion of the results with current sources. Therefore, Table 1 also includes four references published after the empirical study, demonstrating that the multidimensional conceptualisation is still valid in latest research.

to network size in Table 1 could not confirm any associated hypotheses (Chiu et al. 2013; Hsu and Lin 2016; Mouakket and Sun 2019; Schüler 2022). Furthermore, Lee et al. (2006) show that industry-specific factors can hinder the "winner-take-all-hypothesis", reducing the effect of the installed base and thus the total network size. This finding is consistent with the current IIoT platform market state (Lueth 2019). Complementing this, Rietveld and Eggers (2018) show that the heterogeneity of platform actors leads to situations in which additional platform users do not necessarily add value to the ecosystem. Additionally, Chiu et al. (2013) even express concerns that the quality of relationships between platform actors may decrease as network size increases. This effect could also weaken the positive impact of large networks based on digital industrial platforms. Schüler (2022) specifically shows that the network size has no significant effect on the network effect evaluation of digital industrial platforms.

Prior research often distinguishes between the total network size and the availability of valuable partners in the ecosystem. Therefore, we suggest that the measurement of network effects should focus on the ecosystem utility, which is generated only by the availability of valuable platform users from the perspective of other platform users. Supporting this principle, some articles also deviate the dependence of the network externalities concept beyond the simple network size, recognizing additional network characteristics. The structure of the network and composition of the network participants, as well as the ties between network actors also play an essential role, as they directly influence the number of potential nodes and edges in the network (Afuah 2013). In principle, there can be differences in the composition of actors (e.g., in terms of capabilities or reputation) on platforms within one market side or across multiple market sides. Parker and Van Alstyne (2005), for instance, highlight the two-sidedness of network in the real world, recognizing that the end customers' choice is barely influenced by the numbers of other end customers. However, content creators value large end customer networks, and vice versa- The end customers appreciate the size on the supply side due to the associated content diversity. Similarly, Song et al. (2018) consider the specificity of software development and illustrate that developers value platforms with a larger user base, while users value platforms with a larger variety of complements, which potentially create added value through more useful complements. With that in mind, the effects of such characteristics as reputation, unique capabilities, the ability to close structural holes, the centrality of complementors, and their distinctive capabilities or knowledge are reported to influence the network effects (Afuah 2013; Däs et al. 2017; Tang et al. 2020; Haurand 2022). This benefit-creating composition of the network is subsequently referred to as ecosystem utility and should be considered to develop measures of same-side and cross-side network effects. That depends on whether the network actors expect value from other actors from the same side or from the other side.

Analyzing the measurement of indirect network effects in Table 1, prior research shows a more consistent picture, mainly relying on complementarity and compatibility. Indirect network effects result from the availability of complementary products and services, perceived as useful, as diverse as possible, and of high quality (Nair et al. 2004; Kim et al. 2014; Gao and Bai 2014; Hsu and Lin 2016; Rong et al. 2018b). Complementary products and services can directly increase the benefits of the ecosystem. In the past, it was recognized that software complementarity is positively increasing hardware sales (Nair et al. 2004). In the case of digital industrial platforms, the so-called E2E solutions or the associated “smart services” create value through optimized resource use, higher plant output, better quality, and optimized product life and maintenance cycles (VDMA and McKinsey 2020). Alternatively, the benefit of network technology can also be increased via compatibility with other networks and their complements, as in this way, both the users and the functionalities of the connected network technology influence the primary technology (Markovich and Moenius 2009; Zhang and Yue 2020). Due to technical compromises and often high development costs, the degree of interoperability is decisive for implementing interoperable solutions (Farrell and Saloner 1992). Therefore, cross-platform interactions often exhibit inferior quality. One decisive factor is whether the interface is used for unidirectional or bidirectional data exchange (read and write between the systems) (Eisenmann et al. 2009). However, functions do not necessarily have to be developed by the platform provider but can alternatively be provided by various actors in the platform ecosystem. Due to the enormous number of individual solutions and heterogeneous use cases, digital industrial platforms require a high degree of platform openness to ensure that the necessary interfaces and protocols can be developed in time (Ceccagnoli et al. 2012). Alternatively, platform providers can also foster network effects through acquisitions, integrating new complements or interfaces from other networks (Schief et al. 2012). From the point of view of the theory of network externalities, it is secondary whether the platform owner, software development firms, or the end-users of the solution carry out the development. As a result, complementarity must be considered as a source of indirect network effects as it is described as an overall functional scope of digital industrial platforms. To fulfill all possible requirements that users place on digital industrial, the platform must be open enough for other firms to develop complementary products and services (Benlian et al. 2015). The same logic applies to compatibility, which can also be viewed as a source of network effects.

3.2 Conceptualizing a multidimensional view on network effects

The examined literature provides comprehensive evidence that network effects consist of different dimensions. Table 1 shows that research on complementarity has developed straightforwardly and is included in most models since 2012. The compatibility is also used consistently whenever it is included in a model to measure network effects.

The findings are, however, not as clear for network size and ecosystem utility as the effects and operationalizations of network size and ecosystem utility dimensions vary. It appears that network size plays a minor role in influencing network effects since it is commonly mentioned in the analyzed articles only as a theoretical background of the network effect theory. Furthermore, four studies reject every hypothesis related to network size and its implications. To understand this counter-intuitive finding and the reasons why some studies support the dimensions while others fail to, one has to understand the concept of sorting externalities (Peitz 2006). Assuming that the value of every network participant is equal for every other participant, as simplified, for example, in Metcalfe's Law, there is a direct correlation between the overall network size and the value generated by network effects. Nevertheless, the current discussion criticizes this law as incorrect (Metcalfe 2013), which is also true for digital platforms. Since digital platforms can be conceptualized as multi-sided markets, the first restriction to this simplification would be that all network participants on the same side of the platform would prevent interactions and value creation. Additionally, a substantial increase in users on the supply side might increase competition, decreasing the network value for existing users on the supply side (Cennamo and Santalo 2013; Cusumano et al. 2019). Furthermore, the complexity of technological platforms and the specificity of industrial use cases lead to the problem that the network develops sub-clusters, where interactions occur between few partners. This leads to local optima for specific contexts and a minor relevance of the total network size (Lee et al. 2006; Shankar and Bayus 2003; Suarez 2005). Free-riding among complementors is also known as a platform-specific problem (Cennamo and Santalo 2019). Therefore, sorting externalities can determine the correlation between the total network size and the generated network effects. Many studies address this problem by measuring the availability of useful (i.e., offering valuable capabilities and actively innovating) platform users (Afuah 2013; Li and Kettinger 2021). Because all operationalizations of this dimension (e.g., peer influence, number of peers, referent network size) somehow measure the platform's utility based its users, we conceptualize this dimension as ecosystem utility, which only encompasses network participants valuable for co-creation or platform-based interactions (Schüler 2022).

Therefore, we decompose network effects into three dimensions: (1) *ecosystem utility*, (2) *complementarity*, and (3) *compatibility*. A previously performed empirical determination of the dimension weightings indicates that the three dimensions have an almost equal influence on complementor loyalty in the IIoT domain (Schüler 2022).

3.3 Interpreting the network effect dimensions for digital industrial platforms

Figure 3 illustrates the multidimensional view on network effects for digital industrial platforms:

Ecosystem utility: This dimension describes the availability of valuable ecosystem actors using the digital industrial platform. It applies to all ecosystem actor types, ranging from production partners to complement builders. Thus, the question arises to what extent the actors of an IIoT ecosystem can generate benefits from interactions with other platform-using actors. Given that simply pursuing the largest ecosystem leads to strategic contradictions, which in turn may harm the platform's quality, the ecosystem's construction should include a focus of platform activities (Cennamo and Santalo 2013). Therefore, an analysis of the composition of the current ecosystem is necessary to identify actions fuelling network effects. This step should include the distribution of platform users on each side, their behaviour, and the interactions between each other. At first, it is crucial to define which users and properties are required on each platform side to enable interactions. Subsequently, one should develop measures to differentiate active and inactive users to reflect that only active and innovating users support the development of network effects (Schüler 2022). Empirical evidence from digital industrial platforms indicates that passive complementors may enter partner programs and free-ride, simply monitoring the platform development without contributing complements, which is undesirable from the platform provider perspective (Cennamo and Santalo 2019). Conversely, key ecosystem actors can fill gaps in the provision of complex E2E solutions and contribute key complementary subcomponents of such a solution (Afuah 2013). The distinction could be based on each user's monthly expenses or the monthly revenue generated by a specific complementor, to reveal which users lead value creation in the ecosystem. Based on this analysis of different user cohorts, combining different categories can increase the importance of the KPIs in this dimension. In addition, useful platform users are those whose goals align with other users. For instance, an app developer would be useful for a mechanical engineering company wishing to develop a platform-based application for injection molding, while a mechanical engineering company from a different domain (e.g., wood processing) would not be useful. In this aspect, digital industrial platforms differ from B2C as the stimulation of ecosystem utility is more challenging and does not entirely consist of connecting arbitrary platform users in any ratio (Schermuly et al. 2019; Pauli et al. 2021; Chu and Manchanda 2016). Hence, the overarching question of this dimension is whether the platform enables each platform user to find the right partners at the right time (Fig. 3).

Complementarity: Building on the definition from Lin and Bhattacherjee (2008), we define complementarity as the availability of platform-based complements (e.g., applications for vertical use cases) that generate added value for the industrial end customers of the platform. Therefore, complementarity encompasses the functional scope of the digital industrial platform and can be achieved either by the platform provider or the complementors. Yet, complementarity of a platform ecosystem is influenced not only by the number of available applications but also by their quality and novelty (Panico and Cennamo 2020; Hilbolling et al. 2021). Therefore, various compromises must be taken into account when managing digital industrial platforms. First, fundamental governance decisions have to be made as to how the platform leverages the potential of complementary development to leverage industrial use cases on the platform. For instance, a high level of competition amongst the complementors leads to innovations and increasing quality of the complements, simultaneously reducing the incentives to develop complements due to falling margins (Cennamo and Santalo 2013). To tackle this, platform providers could monitor usage statistics when assessing complementarity to balance these effects. For example, if an application is installed in many end-customer shopfloors but has a low customer retention rate, it might indicate a need for additional competition in this area. Additionally, the interplay of different applications used by industrial customers can help identify app clusters and bundle them into E2E solutions, guiding the ecosystem development and revealing blind spots for new complements.

Compatibility: Based on the work of Moore and Benbasat (1991) and Chiu et al. (2013), we define compatibility as the degree to which a technology is perceived as being consistent with existing standards, values, and needs of users. The compatibility of digital industrial platforms comprises the possibility of exchanging data with machines, products, and IS via interfaces and standard protocols. From a technical point of view, interfaces and other integration technologies are essential for connecting the platform core with third-party complements or other peripheral systems, including industrial assets that increase the amount of available data on the platform (Baldwin & Woodard 2009; Ghazawneh and Henfridsson 2013; Beverungen et al. 2020). Therefore, based on connected things or available data, the relevant network size depends highly on the platform's compatibility with other IS and their interfaces or standards (Gallaugher and Wang 2002; Hodapp and Hanelt 2022). The central characteristic of the relevant network is whether the solutions of different ecosystem actors create synergies or can be used together. In the case of operational network goods, whether one service can exchange data with other services or technologies is decisive for the data-oriented network size. If two companies' systems are interconnected or compatible, the total user base of the two systems forms the corresponding network. Following the compatibility definitions of Farrell and Saloner (1992), the use of standards, the standardization of interfaces, or the availability of connectors (e.g., to other platforms or machine controls) of a platform also increases compatibility. Industrial platforms can bolster their compatibility by using open application protocols or specific data converters (Menon et al. 2019; Pauli et al. 2021).

While other approaches to assess network externalities as multidimensional constructs exist (Afuah 2013), they remain theoretical and do not offer platform provides operational control measures. Therefore, to facilitate management of such intangible factors, we perform an empirical study to develop KPIs, enabling performance measurement, and guiding managers in analyzing the effectiveness of governance decisions.

4 Empirical research design

Based on the previously described literature analysis we conduct an empirical study with practitioners to (1) develop KPIs for measuring network externalities, (2) structure and consolidate them in a portfolio (3) reason a management framework based on the KPIs and (4) validate the correctness and the usefulness of the developed KPIs and the framework. Figure 4 illustrates the complete research process:

KPIs are performance indicators capturing specific performance aspects. They enable performance evaluation by comparing it with past performance (Parmenter 2019), aiding decision-makers to navigate strategy (Micheli and Gupreet 2021). Although network effect measurement models in the scientific literature provided information about certain variables, there was not a single study that focused on performance measurement or proposed empirically validated KPIs beyond the network size (Chiu et al. 2013; Tang et al. 2020; Karhu et al. 2021; Schüler 2022). This state of research is not surprising since it is difficult to drive performance measurement in dynamic and sociotechnical settings (Melnyk et al. 2014), like IIoT.

Considering the scarce research on the operationalization of network effects, we opted for a qualitative-empirical research strategy to enrich the multidimensional concept with appropriate KPIs and validate their applicability based on domain-specific insights from industrial platform providers. It is also essential to recognize that operationalizing network effects of digital industrial platforms is a context-dependent task in an emergent environment. For this, direct conversations with experts from platform-providing organizations, who are personally involved and interested in measuring network effects in the context of their platform governance and strategies, seemed to be the most appropriate way to investigate the phenomenon. External observation was deemed unsuitable given the competitive significance of performance measurement for platform providers.

Hence, we engaged with eight carefully chosen digital industrial platform organizations based on specific criteria (e.g., each platform was on the market for years, had an ecosystem of actors, and openly communicated its positive development) to learn if and how they measure network effects. In line with the explanation in Sect. 2, we developed our results with representatives from digital industrial platforms with an innovation focus (i.e., facilitating IIoT application development), transaction focus (i.e., facilitating brokerage of manufacturing capacities and the required transactions), and hybrid platforms (i.e., combination of development technologies and app stores) to identify distinctions between their operational management. In the involved platform-providing organizations and platform-managing business units within incumbent industrial companies, we convinced different organizational roles, such as (platform) product managers, product owners, business developers, ecosystem managers, and CEOs, to participate. All of the invited practitioners had at least 5 years of experience in their industrial sectors, companies, and the platform business and were involved in the strategic and operational platform development so we considered them as key informants. Our data collection consisted of 16 workshops, conducted with a total of eight digital industrial platform providers, arranging two workshops with each. On average, we were successful in inviting two representatives from each platform-providing organization. The first workshop series adapts the goals of exploratory focus groups to enrich the multidimensional concept of network effects based on (1) *KPI development* in moderated group discussions. The second workshop series adapts the goals of confirmatory focus groups, as moderated group discussions are again used to (4) *evaluate the consolidated KPI portfolio and associated platform management framework* by experts for their usefulness (Tremblay et al. 2010; Thoring et al. 2020). Table 2 provides an overview of the experts that were engaged in the two series of workshops.

Therefore, to answer the RQ, we aimed to integrate expert knowledge to understand the operationalization of network effects from the platform provider perspective. Primary data was collected through moderated discussions. Thus, the data collection is characterized by an interpretive character (Walsham 1995), as the experts listened to our interpretation of the network effect theory in the industrial platform context, and we subsequently interpreted the operationalization approaches of the experts.

We conducted the first series of workshops between April and June 2021.[2] In particular, these workshops aimed to explore existing KPIs and foster collaborative development. We questioned the participants about (1) their understanding of network effects, (2) the perceived importance of network effects for the platform business model, (3) the consideration of network effects in the platform strategy, (4) and how network effects were facilitated and (5) measured. After that, we introduced the practitioners our view on the network effects theory and the multidimensional conceptualization of network effects. Following this, we asked how important the experts perceive the network experts to provide value to their platform-using industrial user groups. We then steered the conversations by asking for examples of which manifestations of these dimensions they were familiar with from their practice, and we asked them explicitly how they currently measure network effects or other performance attributes of their platform. All workshop participants could describe the dimensions and think of specific manifestations and related KPIs to measure them. Hence, during the first series of workshops, individual statements of participating experts (Bogner et al. 2009) built the data foundation, especially tapping the questions of which KPIs are used and how the presented network effect dimensions could be measured. Some platform providers confessed difficulties in measuring specific aspects of network effects (#1 "*I would not have thought that it would mean such a change in thinking for them to include third-party products in opportunities*.") or admitted not measuring network effects at all (#8 "*The answer is quite simple—we do not measure anything at the moment concerning the platform*"). In such cases, the procedure was to develop potential KPIs on the preliminary understanding of the research team. When developing KPIs during the workshops, the research team mainly brought in the variables from the literature sample and their expertise around digital industrial platforms to help practitioners reflect on their experiences and formulate potential KPIs.

The workshop recordings and memory protocols were transcribed. With the help of transcripts and protocols, qualitative content analysis about each KPI across all workshops was performed, guided by the network effect dimensions as a classification scheme (Gläser and Laudel 2010). Table 3 presents the coding procedure using illustrative statements.

After the first workshop series, we assigned the elaborated KPIs to the three network effects dimensions. In addition to these three dimensions, KPIs were determined in relation to the demand and supply sides. Distinguishing both market sides provides insights into whether between-group effects exist. Considering the multiple platform-related tensions, this helps to measure whether the performed governance measures lead to growth on both market sides or create opposing growth effects. The reasoning process also revealed that many network effect aspects were not considered by the platform-providing organizations from the sample in their platform development. Accordingly, between the workshop series, we reflected on these blind spots of each platform provider and, following the principles of abductive discovery

[2] The workshop materials were pre-tested with experienced scientists from the platform economy and financial accounting research fields and are available upon request.

(Kathuria et al. 2020), crafted a consolidated KPI portfolio. Besides, we decided to drop all of the co-developed KPIs that require an additional social network and are not directly measured on the digital industrial platform (e.g., ecosystem interactions on LinkedIn).

New topics were expected to emerge from the data in line with abductive reasoning. During the workshops, practitioners expressed the need to monitor the financial performance of the platform. This viewpoint became part of the discussion in workshops, as the measures discussed to promote network effects may incur costs and reduce the financial profit of a platform provider. The practitioners cited cases such as Amazon, known to have grown its ecosystem for years without considering the negative impact on profit (Kenney et al. 2021). This resulted in a new dimension, which reflects the earnings perspective of the platform provider. The experts actively proposed some KPIs for this category, and some KPIs were integrated into the KPI portfolio by the research team in consultation with senior controlling researchers. The contrasting structure of the consolidated KPI portfolio between the network effect dimensions and the earnings perspective (see Fig. 5) was supported, for example, by statement #9 in Table 3.

Furthermore, abduction helped to recognize the inherent conflict between fuel network effects and the organizational financial performance. The practitioner statements about their firms' concerns about profitability, while having either no financial means or no approval to subsidize an unprofitable business unit (e.g., due to the structure of the shareholders) as long as it is necessary. Compared to the literature (Stummer et al. 2018; Tiwana 2014), the importance of the earnings perspective to the practitioners emerges as an important aspect of platform establishment. Thus, abduction led to more generic propositions, resulting in a framework (see Sect. 5.5) that utilizes KPI-based performance measurement and was found helpful for platform providers.

Building on these results, additional confirmatory workshop series with each industrial platform participant was conducted between July and August 2021. Since the KPIs were interpreted by the research team, a consolidated KPI portfolio was presented for cross-case evaluation from practitioners, helping to understand its generalizability. This was also an opportunity to present the abducted framework, which was used as a working document to prove its utility. We also expected to evaluate if and how each platform organization could benefit from applying the framework. Therefore, the second series of workshops intended to achieve a proof-of-value evaluation by discussing the artifact value under the moderating control of the researcher team. Thus, after explaining the framework, we let the experts reflect upon it by thinking about their specific platform context, leading to the final refinement of the portfolio and the framework. The discussions were open, but the qualitative evaluation criteria, such as usefulness, limitations, and requirements for implementation, were part of specific questions during the discussions to evaluate the suitability of the KPI portfolio and the framework for the practitioners.

To mitigate the descriptive validity threat, two researchers attended the focus groups to support each other in construct conception, questioning, and observation. Considering the data analysis, both researchers coded the workshop transcripts independently and iteratively to ensure a shared understanding of the collected data. While researcher bias is inevitable, we believe the literature review before the workshops served as a safeguarding factor and contributed to the objectivity of the results on measuring network effects. In addition to the literature review on network effects measurement, the research team's prior understanding of KPIs was supported by Parmenter's standard work on KPIs (2019). We employed the second round of workshops to ensure construct validity and evaluated the conceptualized KPIs and their unrestricted suitability for each company by presenting them to the practitioners and discussing whether they could be applied. A control by practitioners aimed to include only those KPIs in the final result that measure the right thing and to reduce the risk of losing clarity regarding network effects development and platform profitability (Parmenter 2019). This led to a reduction and consolidation of KPIs, possibly neglecting further indicators.

5 Network effect KPI portfolio for digital industrial platforms

This section presents exemplary KPIs for the three previously conceptualized dimensions of network effects and the framework for platform management drawing on them. Figure 5 illustrates a consolidated KPI portfolio for every dimension, which can be used to develop an individual platform management cockpit. The final portfolio incorporates 20 KPIs for measuring network effects, contrasted with the earnings perspective and the corresponding KPIs for financial management.

5.1 Ecosystem utility

Instead of focusing on the absolute numbers of platform users that are likely to include inactive and thus, not valuable users, an evaluation of *active platform users on the demand side (AUDS)* should be carried out to identify the most valuable ones. Active users can be defined as companies exceeding a defined threshold of monthly fees or, on a technical level, addressing the frequency of data exchange or the number of transactions with the platform core. It would mean that industrial end customers, for example, actively use the platform and process the machine data on it. A similar KPI frequently used in practice to measure ecosystem utility is the *customer retention rate (CRR)*. Adapted to digital industrial platforms, CRR represents the number of platform-using end customers or complementors that a platform provider retains over a certain time period. Each platform user in the ecosystem represents a node in the network, which lays the foundation of the utility of the ecosystem. A suitable formula to measure CRR calculates a difference between the numbers of end customers at the end of a measurement period and the beginning of the measurement period taking into account new customers.

Although not specific to IIoT, *Net Promoter Score (NPS) was another* derived KPI to approximate ecosystem utility for both sides. When evaluating the NPS data, promoters (rating = > 9 on a scale from 1 to 10) must be subtracted from detractors (< = 6). This absolute number should grow steadily to measure a positive impact on network effects. Despite the criticism on NPS (Fisher and Kordupleski 2019), an increase in the NPS while other factors such as service quality or pricing are constant is a clear indicator of an increase in ecosystem utility with useful ecosystem partners building the source of satisfaction. Therefore, it is additionally necessary for the platform provider to isolate the sources of satisfaction. Although this KPI is not IIoT-specific, it was explicitly mentioned by experts because ecosystem partner satisfaction is essential in each domain from the platform provider perspective (Petrik and Herzwurm 2020). To measure NPS, appropriate modules for data collection are added into the interface of the complements or the platform.

In addition to the end-user perspective, the *absolute number of active complementors (#AUSS)*, who provide integration services for industrial customers and create value-added complements, should be measured. After all, this increases the implementation capacity for industrial end customers in the IIoT, who bind many complementor capacities in complex smart factory projects. In addition, it is advisable to measure the *heterogeneity of the complementor landscape* by defining complementor types. Typically, higher heterogeneity is beneficial for implementing heterogeneous use cases and the added value of a platform for industrial end-users (Parker et al. 2017; Hanelt et al. 2020). Another indicator of growing network effects is the positive development of the absolute number of *leads generated by complementors* (such as system integrators). Complementors conduct the more platform deployments for industrial end customers, the more nodes exist to increase network effects, while passive complementors do not increase the performance of the ecosystem.

5.2 Complementarity

To measure the complementarity of digital industrial platforms from an end-user perspective, the *absolute number of complements* is a reasonable and rewarding KPI to justify expenditures for ecosystem and partner development. However, this measurement does not provide information about the usage of these complements. Therefore, we recommend measuring complementarity by tracking numbers of application downloads or installations within the industrial end customer' factories. This measurement considers that only actively used complements foster network effects. Therefore, the *absolute number of complements* that exceeds a *certain threshold in the number of end customers using it* is a suitable measure. Based on this data, platform providers can better understand which use cases and required functions are mainly used on the platform and how they are aligned with the current platform strategy. The experts from almost every digital industrial platform provider stated they were able to monitor *the usage statistics of the complements* to gain essential insights for platform management, measuring the number of app launches, the duration of app use on the system and the CRR on the app level to derive patterns of platform use and compare them over time.

If the platform has a rating system for complements, the *absolute number of complements that have a better average rating than a certain threshold* can be another pervasive indicator to support complementarity (Steur and Seiter 2020). However, depending on the individual use case, this KPI cannot always be monitored in a reasonable way. The *exclusivity of the platform-based offerings* is another illuminating indicator for the complementarity dimension, as exclusive complementarities can have a magnetic effect on attracting new platform users, promoting network effects. Exclusivity can be mapped via an index by dividing the number of exclusive complements by the number of all complements. Strong network effects and lock-in effects arise when the most used applications on the platform are exclusive. However, because value creation in some platform ecosystems is primarily fulfilled by a few successful complementors (Hyrynsalmi et al. 2016), the exclusivity of platform-based offerings should only be a subordinate target. After all, despite the migration costs multihoming can barely be prevented in IIoT practice and is an effective safeguarding strategy for complementors (Chen et al. 2021). In line with Foerderer et al. (2019), the *update frequency of the complements* can also be measured since a growing update frequency across all complements indicates an increase in innovation capacity and reflects the activity level of the platform-based value creation.

From the end-user perspective, *the absolute number of industrial assets and systems* that are connected to the platform is a pivotal KPI for measuring complementarity. This KPI can be approximated based on active licenses and device tokens. This number should steadily increase to facilitate network effects. To get a deeper understanding on how the platform is used in different companies, *the number of simultaneously active assets and devices in the industrial shopfloor* can be evaluated. The more assets exchange data with the platform, the higher the data consistency and the higher the potential benefit of the platform for each end customer. Therefore, growth in active assets is an important metric to promote value creation by complementors.

5.3 Compatibility

In terms of compatibility, the *number of connectors* provided for and by complementors can be an additional indicator for a positive development of the compatibility dimension. In many cases, the number of actively used connectors that exceed a defined threshold of active users yields better information than the simple number of existing connectors as the intensity of use indicates the value from each connector. Connectors provided "out of the box" by the platform provider also positively affect the diffusion of digital industrial platforms in industrial operations. In addition to aggregating API calls, the usage intensity for each connector can be measured, for example, by the total number of industrial assets exchanging data per connector or the total number of industrial assets exchanging data with the platform via a specific connector at the same time increasing the amount of industrial data on the platform available for complements (Beverungen et al. 2020).

Considering the complementor side, the *number of assets and industrial devices natively supported by the platform and optimized for data exchange with the platform* can indicate how strongly other companies assess the network effects and the platform's potential. Besides, the *number of active connection to other systems or platforms* that were realized by complementors can be counted. This KPI also helps to determine active and therefore valuable complementors.

5.4 Financial focus

During the workshops, the experts also raised the financial efforts required to stimulate the network effects along the three dimensions. Therefore, financial KPIs should be tracked to understand the financial effects of the measures aiming to stimulate network effects. The derived KPIs are distinguished between an operative management perspective and a reporting perspective, enabling comparability between the platform and traditional business models.

Unit economics and their development play an important role in validating the business model of digital industrial platforms as the ecosystem grows and giving clear indications about the long-term profitability of the platform. Unit economics refers to the revenues and costs related to an individual unit of production. For digital industrial platforms, the unit can be a specific platform-based transaction or the integration of a new machine or partner. A steady decrease in unit economics indicates the increasing scalability of the platform. While unit economics calculation is relatively simple for transaction platforms (i.e., the number of orders placed via the industrial marketplace vs. the acquisition costs of the industrial end customer), the value creation in innovation-oriented platforms will often prevent a low expenditure calculation. Therefore, the ratio between the *cumulative turnover generated by the supply side (ΣTUSS)* and the *number of active users* is another way to analyze the value creation in the platform ecosystem based on financial data. Similarly, the *customer lifetime value (CLV)* can be calculated in the context of the financial performance of an end customer. The CLV indicates how much value a customer has generated on average since the start of platform use based on the revenues (Berger and Nasr 1998). In the IIoT, factory operators are conceivable here, who increasingly connect further production areas or plants to the platform or bring the integrators of their choice onto the platform. This KPI can either be calculated purely on the revenues (i.e., contribution margin) of this customer or include the platform-based revenues of other users who were brought into the network by a specific user or application, which can be understood as the *customer lifetime network value (CLNV)* (Däs et al. 2017). Ultimately, the CLV per client must increase over time to show a positive development of the interactions on the platform. Based on the behavior on the user level (e.g., expenditure), statistical analyses are used to define user cohorts to make platform offerings more targeted.

For the supply side, an increase in *cumulative turnover* of all complementors indicates value creation in the ecosystem and is a clear manifestation of indirect network effects on the platform. Compared with the platform providers' own sales, the cumulative sales of the complementors should exceed them and also also increase faster in order to reflect a positive development of the network effects. In addition, the *proportion between the platform provider's own complements and the partners' complements* can be measured. This ratio should change in favor of the apps created by partners to foster network effects and can monetarily be addressed with the quotient of the turnover of the platform operator and the cumulative turnover of all complementors. Moreover, if the platform operator is a multicorporate enterprise with a diverse product portfolio, in line with industrial incumbents' platform establishment goals (Marheine and Petrik 2021), the *sales of the platform provider's other business units and products* should also be monitored to measure how the platform integration affects them. Based on these vertical complements, owned by a platform provider with a broad product portfolio, network effects around different use cases or industries can be positively influenced as the products can develop new value-added aspects through the platform and thus attract new product customers. The connectivity between manufacturing and logistics units can be extended, or new insights from industrial process data captured and forwarded to the platform can be generated are examples specific to IIoT.

To close the gap between the reporting of specific requirements of platform-based and traditional business models, the intermediate and long-term targets of all platforms in our sample were represented by standard KPIs such as the *turnover of the platform*, the *annual recurring revenue (ARR)*, the *return on invest or the EBIT* as well as the *EBITDA*. These KPIs indicate the financial success of a platform, especially in the late stages of a platform lifecycle. However, additional financial KPIs for platforms can be adapted from the study by Illich-Edlinger et al. (2021).

Following the logic of the operationalized network effect dimensions that can be measured by platform organizations in the industrial domain, in the next section, we further conceptualize a framework to steer digital industrial platforms in a balanced way.

5.5 Framework for a balanced performance management

Unlike in product business models, value facilitation mechanisms in platform-based ecosystems require the management focus to shift from maximizing the platform provider's profit alone to maximizing the profits of the entire ecosystem, thereby increasing network effects (Ceccagnoli et al. 2012; Schreieck et al. 2017; Cennamo 2019). Various measures can be employed by platform providers in the IIoT domain to increase network value, including investment in customer onboarding or boundary resources deployment to subsidize the various platform user groups (Lin and Whinston 2011; Svahn et al. 2017; Stummer et al. 2018; Marheine and Petrik 2021). However, experts explicitly stated the costs for the platform and ecosystem development (Tiwana 2014; Huber et al. 2017) incurred during platform establishment in competitive environments like IIoT. These costs pose a serious factor depending on the firm's size. Industrial incumbents operating digital industrial platforms often lack access to capital markets, unlike their counterparts in B2C domains, or face conservative investor expectations when they do have such access. Therefore, digital industrial platform providers face a trade-off and must decide whether they increase the earnings as more value is generated for the users or maintain their pricing level to boost consumer surplus and attract additional users.

To manage this trade-off, platform firms must balance growth based on network effects and financial performance (Chen et al. 2021), so we recommend the following approach. To foster network effects and solve the chicken-egg-problem in the early phases of digital industrial platform establishment, platform providers should first neglect financial performance and prioritize value co-creation in the platform ecosystem (Eisenmann et al. 2006; Stummer et al. 2018). To achieve this, platform providers should enhance the ecosystem utility, complementarity, and compatibility since all three network effect dimensions equally impact the perceived value in IIoT (Schüler 2022). Moreover, the prevailing interdependencies between the multiple user groups in platform ecosystems must be incorporated. Therefore, measuring the three dimensions from the perspective of each relevant user group (i.e., market side) is advisable. Thus, to nuance the trade-off between the costly network effect stimulation and the platform earnings—a challenge particularly faced by managers in industrial incumbent organizations during platform establishment—we propose a framework for balanced platform management (see Fig. 6), which utilizes the objectives of the balanced scorecard. A balanced scorecard has been adapted to measure the success of IS in the past (Martinsons et al. 1999), and one of its objectives is to guide managers in following long-term strategies, shifting the focus away from purely short-term financial metrics (Kaplan and Norton 1996). Accordingly, the framework emphasizes the necessity of balancing between the two contrasting perspectives and the different market sides when facilitating platform-based value creation for each side to establish a platform in the long term.

However, specific actions on the operational level must be performed to achieve a certain platform strategy. Managers are required to implement a performance measurement that captures the network effects as a platform growth factor. To achieve this, the empirically developed KPI portfolio helps to implement platform performance measurement, tracking the development of the network effects and the financial performance of the platform.

To explain how the framework works, we use exemplary KPIs from the complementarity dimension from both market sides. In this case, the value creation for complementors through industrial end customers can be addressed with the total number of application downloads per period. On the other hand, the increasing number of complements indicates the value created by complementors for the end users. The derived KPIs should be monitored and evaluated in recurring time frames (e.g., monthly, quarterly) to continuously measure the network effect stimulation and prevent unilateral platform development, which can lead to negative network effects (e.g., oversupply). To preclude them, the rates of change in all three dimensions compared to the prior period must be positive in all fields of the portfolio.

After the successful implementation of measures and the proof of positive growth rates in all three network effect dimensions for each side during the initial platform establishment phases, the earnings perspective may increase its importance to enable the platform to pay itself. Regarding the earnings perspective, platform providers have to decide whether the additional value in the ecosystem generated by network effects should be used to increase network effects even more due to the inter-platform rivalry (Cenamor 2021) or improve the platform's financial performance as a business model. The first option leads to ecosystem growth and facilitates a long-term increase in platform earnings. However, most early-stage platforms support growth by subsidizing user groups, dropping revenue growth. Microsoft, for example, spent a large budget to grow the developer ecosystem for Windows

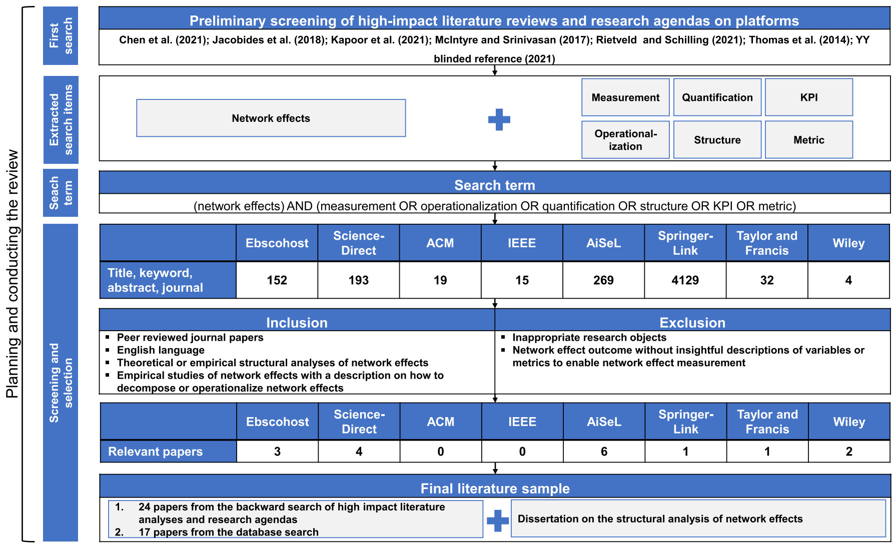


Fig. 2 Systematic literature review process for subsequent conceptualization

Phones without great success (Cusumano et al. 2019). Accordingly, we conclude that due to the high costs of developing and maintaining digital industrial platforms, the revenue streams have to be adapted over the life cycle to achieve the long-term profitability of the platform. Therefore, increasing the prices as the value of the ecosystem grows in the later phases of the platform lifecycle is a reasonable strategy to balance the cost–benefit ratio for platform users and increase the platform's earnings (Tiwana 2014; Cusumano et al. 2019), which may help industrial incumbents or organizations with smaller budgets or without access to the capital market to establish platforms.

To implement this strategy, the subsidies must be reduced, or the platform access price must be increased. Both options have a direct negative impact on all three network effect dimensions and must be carefully implemented. Suppose the negative effects on the network effect dimensions exceed the additional value created in the ecosystem. In that case, network effects become negative, the innovation platform ecosystem dynamics shrink, and the financial performance worsens. If, for instance, the platform access becomes too expensive for system integrators, they can look for other platforms and advise their industrial customers to migrate as well, as platform substitutes also exist in IIoT. Consequently, implementing KPI-based performance measurement, platform managers should become sensitive to the incentivization of platform users (Ceccagnoli et al. 2012), preventing network effects from reaching negative downtrends and securing a positive growth rate of the network effect dimensions.

Thus, platform managers have to decide not to slow down the network effect growth while the platform business model may not be profitable on the one hand and to take such measures to stimulate the network effects on the other hand, balancing the trade-off between the financial performance and the stimulation of the network

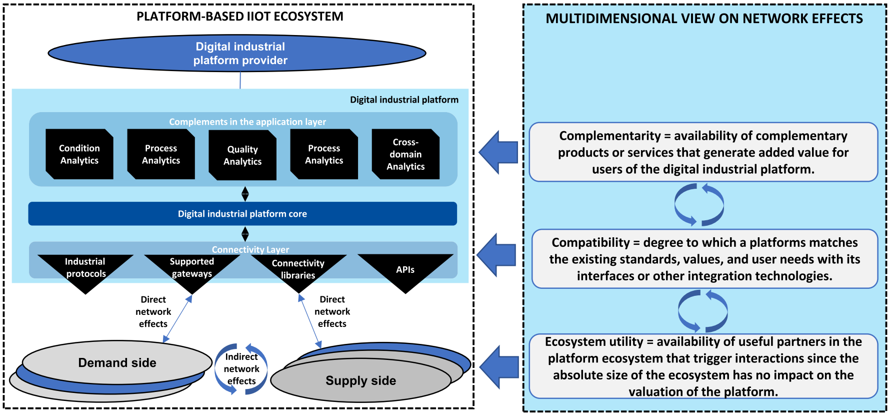


Fig. 3 Multidimensional View on Network Effects for Digital Industrial Platforms

effect growth. Especially in markets with intense competition, such as IIoT, platform growth can quickly end. In addition, promoting ecosystem utilities through subsidies may, for example, attract too many complementors, reducing their incentives to innovate (Cennamo and Santalo 2013). Promoting connectivity, for example, may encourage platform user migration to other platforms and favor competitors' strategies, such as piggybacking (Dou and Wu 2021). Furthermore, it is still conceivable that the promotion of complementarity may lead to a decline in security at the complement level, which is critical in the context of digital industrial platforms (Pauli et al. 2021). This implies diverse optimization problems for platform providers in platform-mediated markets such as IIoT.

6 Discussion

Using the empirical context of IIoT, we propose a multidimensional view on network effects that is supported by KPIs and considers the financial aspects of the network effect stimulation. The results are consolidated in a KPI portfolio, which enables performance measurement of network effects to achieve balanced platform management. The data proves that digital industrial platform organizations are aware of network effects as a possible driver of platform growth. In line with the lack of literature on business-relevant network effect operationalization and the positive feedback in the confirmatory workshops, the results also confirm that digital industrial platform organizations experience difficulties establishing KPI-based performance measurement beyond the financial metrics required for reporting. Thus, the results bear significant implications for platform managers and will likely bolster further research and the diffusion of performance measurement in platform organizations.

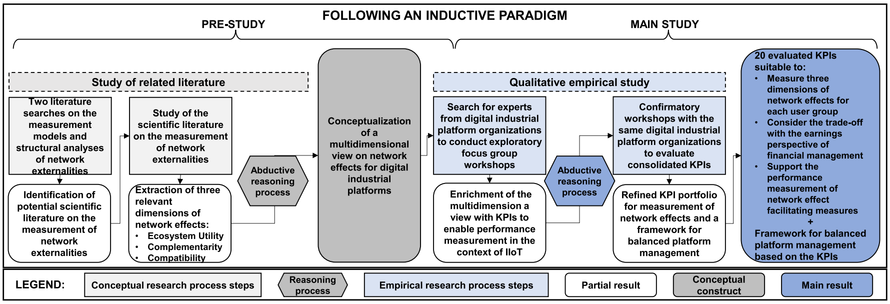


Fig. 4 Detailed Research Process Overview

6.1 Implications for practice

This section demonstrates how the framework and the KPI portfolio, comprising a practical artifact for platform managers, can be applied in practice. Numerous firms utilize balanced scorecards to steer their businesses (Hoque 2014; Nørreklit et al. 2012; Lueg and Carvalho e Silva 2021) since they are known to support managers in shifting the focus away from short-term cost reduction to long-term opportunities to increase shareholder value (Martinsons et al. 1999), and advocate the inclusion of non-financial metrics (Kaplan 2012). In incumbent firms with diverse business units, balanced scorecards can be used to measure operational, managerial, and strategic performance levels (Lohman et al. 2004). Hence, the adaptability of balanced scorecards, enabling them to be customized based on the targeted level of a specific firm context, constitutes another advantage (Kaplan and Norton 1996; Kaplan 2009).

The proposed artifact brings similar advantages for digital industrial platform providers. Especially in incumbent firms, platform managers might struggle to demonstrate the financial feasibility of the platform to the executive board, given the absence of rents due to intense competition among platform providers (Cusumano et al. 2019). Overall, the development and integration of interfaces (*compatibility*) and the involvement of relevant partners (*ecosystem utility*) are significant cost drivers for a digital industrial platform provider. This challenge is magnified when a continuous subsidy of the platform or price competition, as was the case with AWS and Microsoft (Gustavsson and Ljunberg 2019), contradicts the overall corporate strategy in incumbent firms and led to the abandonment of the industrial platforms like Predix in the past (McGrath 2020).

This is where the balanced platform management approach proves useful. Initially, the artifact enables the platform manager in an incumbent firm to define a growth platform strategy based on network effects and track the performance based on the three conceptualized dimensions.

By advocating three non-monetary dimensions of network effects, the proposed framework allows a platform manager to justify the budget allocated for the platform business unit since each of the three dimensions supports a continuous measuring of the operational growth targets. For instance, ecosystem or partner managers can pick the KPIs relevant to their platform along the *ecosystem utility* dimension from the portfolio. They can identify and address factory operators (i.e., end customers) with decreasing usage intensity based on the volume of shopfloor data processed on the platform. Regarding *complementarity*, customer success managers can monitor the adoption of applications among factory operators. If the number of connected assets ceases to grow, these customer success managers can specifically assist customers with fresh ideas from other factories. Conversely, product or quality managers can engage with the application creating complementors that have not seen updates for a longer period, aiming to uncover the root causes of problems. Platform architects can, for example, examine the usage data from the connectors offered to other platforms and industrial controllers. A decrease in usage levels might indicate problems in the connector design. Also, prolonged intervals between the customer's payment for a connector and the first data transmission might indicate deficits in platform *compatibility*. When the KPIs are implemented in a holistic performance measurement system, all these operational roles can measure the performance to ensure alignment based on interactions (e.g., a platform architect and a customer success manager integrating new use cases) across the network effect dimensions. Therefore, the framework adds prescriptive knowledge by highlighting the necessity for a balanced approach rather than solely pursuing aggressive user engagement. In particular, it highlights that a platform strategy must simultaneously address three objectives: continuous sensing of useful platform users, consistent with the complementarity dimension, and the simultaneous organization of platform interfaces. Neglecting any of these network effect dimensions will inhibit self-reinforcing growth.

This should help digital industrial platform providers who have not yet generated sufficient network effects (Marheine and Petrik 2021). The KPIs can also be used to educate the employees in the platform business unit to evaluate if the intended business objectives are met and understand how the different operational measures can be leveraged by other measures. Thus, it helps to implement the platform strategy in operational processes.

Going beyond the evaluation of the single measures, in the third step, the artifact might help platform managers in communicating positive platform development, even in the absence of substantial earnings in the short-term, countering the traditional nature of financial reporting, according to which the platform would be more of a candidate for being discontinued by the executive board. Thus, the artifact guides management attention on non-monetary yet meaningful long-term opportunities (Martinsons et al. 1999) offered by network effects.

It also helps balance these opportunities against the costs associated with the network effect promotion (Kaplan and Norton 1996), establishing causality between operational measures, KPIs, and budget allocations. Accordingly, in the fourth step, the artifact forms the basis for budget allocation decisions by the platform manager, the financial controlling, and the executive board. This is important, as incumbent firms often set up the platform business unit as a profit center expected to become self-sustaining within a relatively short timeframe (Marheine and Petrik 2021). In such an organization, middle management is tasked with generating executive board

Table 2 Overview of experts participating in two series of workshops

Nr	Platform type	Architectural foundation	Company back-ground	Geography	Enterprise size	# of experts	Organizational roles of participating experts
#1	Hybrid	Cloud	Software company	Germany	Midsize	3	Platform portfolio manager; Technical assistant; Platform expert
#2	Hybrid	Edge	Industrial company	Germany	Midsize	1	Platform ecosystem director
#3	Innovation	Edge	Industrial company	Germany	Large enterprise	2	Senior portfolio manager; Area owner for industrial edge
#4	Innovation	Cloud	Software company	Germany	Midsize	3	Principal product manager; Key account manager; Account manager
#5	Innovation	Cloud and Edge	Industrial company	Germany	Large enterprise	2	CEO; Ecosystem architect
#6	Hybrid	Cloud	Software company	USA	Large enterprise	1	Strategic alliances director
#7	Transaction	Cloud	Software company	Germany	Smallsize	1	CEO
#8	Innovation	Cloud	Software company	Germany	Midsize	2	Head of partner management; CEO

Table 3 Overview of the data structure and the coding process

Coding scheme: Open coding of transcripts and protocols to identify the already measured KPIs or relevant concepts and categories that build a basis to conceptualize additional KPIs

ID	Illustrative statement with an open code	Sub category	Category
1	#3: "*We make clear to the partners which conditions they have to fulfill in order to be our exclusive partner*"	Leads generated by system integrators	Ecosystem utility—complementor side
2	#7: "*Acceptance rates of orders, how are reclamation rates, how are the delivery loyalty rates, which already I think very strongly pays into this topic of utility? Well, if we now simply take a supplier that has poor delivery reliability and high reclamation rates, then utility is simply super low*"	Order cancellation rate	Ecosystem utility—complementor side
3	#1: "*And I'm sort of counting the apps that are available now: how many proprietary apps do we have in the store and how many party apps do we have in the store*"	Exclusive applications	Complementarity—complementor perspective
4	#4: "*So if now ten ERP providers decide to make their ERP system compatible by serving the interfaces of (our platform), then we would not provide more connectors on the platform side, but the ERP provider or an ERP service provider would say, I have provided the connector to connect x other systems. That would be considered equivalent to systems on the platform,* "	Available connectors to external systems	Compatibility—complementor side
5	#1: "*I'm still a little bit driven by the interaction on LinkedIn. At the half-year anniversary of the ecosystem, we now have 6500 views on LinkedIn. And here, partners have also started to comment, which I also measure for something like that*"	Active users	KPI dropped as not directly collected on the digital industrial platform
6	#3: "*So we have a membership fee in our ecosystem, which is calculated on the basis of license sales as a percentage. And therefore, we already get to know how many license contracts are generated with which customer*"	Unit economics	Earnings perspective—End user side
7	#7: "*Yes, it is still very important for us (…) the development of the cohorts. So more or less, how do the individual cohorts develop, how does the turnover develop and how does the big profit develop over time?*"	Development of user cohorts	Earnings perspective—End user side

Table 3 (continued)

Coding scheme: Open coding of transcripts and protocols to identify the already measured KPIs or relevant concepts and categories that build a basis to conceptualize additional KPIs

ID	Illustrative statement with an open code	Sub category	Category
8	#8: "*Correct. Acquisition costs. You have infrastructures, of course, that you have to provide to the customer. So really the issue of what you said as well. Demo? Yes. … Advance performance? Yes…*"	Unit economics	Earnings perspective—End user side
9	#5: "*I don't know of any platform that has been globally accepted that hasn't sunk several billion first. … I have a certain budget to allocate, I can exert a positive influence on my network effects in order to exert a positive influence on my financial scope. … But in the mechanical engineering it is so that each crisis leads from the VDMA to savings programs and we must already justify ourselves for the expenditure plans*"	Awareness of financial efforts for network effect stimulation	Earnings perspective

Network Effect Focus	Side One (end customer perspective)	Side Two (complementor perspective)	Target (Δ prior period)
Ecosystem Utility	▪ Active users demand side (#AUDS) ▪ Customer Retention Rate (CRR) ▪ Net Promoter Score (NPS) ▪ Average usage frequency per active user	▪ Active users supply side (#AUSS) ▪ Net Promoter Score (NPS) ▪ Order cancellation rate ▪ # leads generated by system integrators	Δ > 0
Comple-mentarity	▪ # application downloads/installations ▪ Usage statistics (#App starts, app usage duration, App level CRR)	▪ # applications > X continuous users ▪ # apps/complementors with Rating > X Stars ▪ # Exclusive Applications ▪ Frequency of application updates	Δ > 0
Compatibility	▪ # of connected industrial assets/machines ▪ # active devices per time ▪ Turnover associated with specific interface	▪ # available connectors to external systems with > X continuous users ▪ # active connections to external systems ▪ # devices optimized for platform integration	Δ > 0
Financial Focus	**Side One** (end customer perspective)	**Side Two** (complementor perspective)	**Target** (Δ prior period)
Management Perspective	▪ Unit economics ▪ Turnover per active user (ΣTUSS/#AUDS) ▪ Customer lifetime value (CLV) ▪ Development of user cohorts	▪ Cumulative turnover supply side (ΣTUSS) ▪ Turnover relation platform owner / complementors (PTO/ΣTUSS)	Δ > 0
Reporting Perspective	Platform turnover operator (PTO), Platform ARR, EBIT/EBITDA, Return on Investment and others		Δ > 0

Fig. 5 KPI portfolio for performance measurement of network effects

stamina for continued investments in the platform and the associated business unit of the incumbent firm (McGrath 2020).

The flexibility inherent to a balanced scorecard allows the artifact to be tailored according to the platform scope. Given the previously mentioned heterogeneity of digital industrial platforms on the market (Lueth 2019; Arnold et al. 2022), not all elaborated KPIs may be applicable. Therefore, following recommendations by Lueg and Carvalho e Silva (2021), "Appendix A" contains a template that platform managers can customize in collaboration with platform operations to flexibly support the performance measurement of the most relevant network effect dimensions based on the metrics agreed upon at the strategic level. The template also assists in customizing the performance measurement system, for instance, to reflect the different types of complementors and end customers, which vary greatly in IIoT. The artifact can be used as the input for the target visualization board of the firm if IT departments integrate the KPIs in a way that will interactively appear in these boards. Implemented in such a way, the artifact could become an early manifestation of the theoretical concept by Bogodistov and Moormann (2020), who argue that IS can help filter and process information to develop a firm's internal heuristics. The trade-off nature of the framework will help platform managers avoid ineffective decisions, having an impact on a firm's future.

Especially in incumbent firms with heterogeneous offering portfolios and multiple business units, balanced scorecards might build a cascading system to link operations with the overarching strategic management system (Kaplan and Norton 1996; Kaplan 2009). In this context, our artifact might aid platform managers in integrating the platform business unit into such a system and aligning it with the strategic level. This is achieved by providing causal schemas between operational measures, the platform business unit budget, and the overall contribution of the platform to the strategic goals of the incumbent firm (Kaplan and Norton 1996; Nørreklit et al. 2012).

On a more detailed level, the framework for balance platform management is designed to provide interactive decision support (Kaplan 2009) concerning the

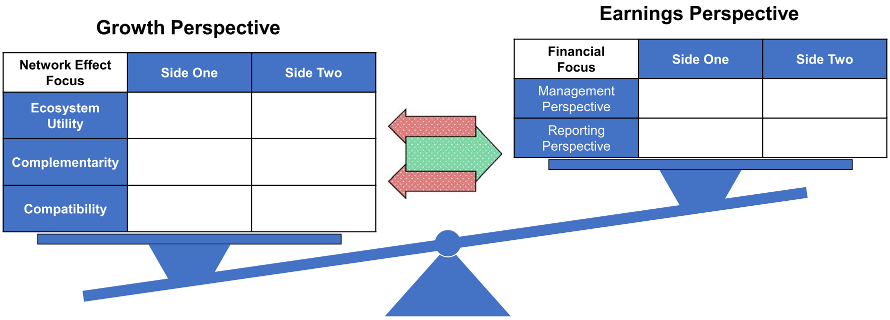


Fig. 6 Framework for balanced platform management

interrelationships of different network effect dimensions and the managerial perspective on platform-based earnings. It suggests keeping a balance between stimulating network effects and the platform financial performance by setting the three dimensions of network effects in relation to the financial outcomes for all market sides. As a result, it assists the strategic level in understanding the platform growth based on the network effects and helps the operational level understand whether the network effect stimulation measures work.

6.2 Implications for theory

On a theoretical level, our study contributes to the literature on network effects, digital platforms, and performance measurement. First, regarding the research on network effects, the study contributes to the developing research stream, which urges the scholars to question the established narrative and rethink the network effects beyond the simple size of the ecosystem (Afuah 2013; McIntyre and Srinivasan 2017; Karhu et al. 2021). The study offers a more differentiated understanding of network effects by conducting a literature-based structural analysis and deriving three equally significant (Schüler 2022) dimensions: *(1) ecosystem utility, (2) complementarity, and the (3) compatibility*. The multidimensional view proves that the decomposition helps to cope with the specifics of the industrial platform domain during operationalization. In particular, the decomposition of the network externalities helps to assess this construct and to distinguish influential dimensions (ecosystem utility, complementarity, and compatibility) from the less influential ones (network size). Hence, this extension of the theory on network effects may substantially increase its explanatory and predictive validity in future empirical studies. Although our study is not the first to propose a multidimensional structure of network effects to improve their measurability (Afuah 2013; McIntyre and Srinivasan 2017), there are two significant differences compared to prior research. On the one hand, our research is devoted explicitly to the industrial platform context, capturing its moderating specifics, such as the individuality at the complement and inter-firm relationship levels, the increasing role of complementary use cases, and the prevalent lack of interoperability. On the other hand, it adds empirical data to the predominantly conceptual research stream on network effect decomposition (Afuah 2013; McIntyre and Srinivasan 2017; Karhu et al. 2021), extending the multidimensional view with measurable KPIs that can be implemented in platform management operations. Since the impact of network effects differs by context (Basu et al. 2003), the applied domain instantiation increases the validity of the results on the structure of network effects. Besides, our study is among the few to answer the research call on network effects by Pauli et al. (2021), contributing interdependent dimensions of network effects and KPIs to measure them. The findings on the empirically confirmed structure of network effects complement the rare findings on the impact of network effects in IIoT (Schermuly et al. 2019; Menon et al. 2019; Marheine and Petrik 2021). The structural decomposition of the network effects and the KPIs can support researchers and practitioners in balancing conflicting outcomes in the management of digital industrial platforms and researching them. The portfolio also demonstrates that certain KPIs (i.e., number of complements or the NPS), well-known from B2C, can be reused in IIoT. Considering the platforms with a transaction focus (i.e., industrial marketplaces), we show that industrial marketplace providers could also profit from internalizing complementarity and compatibility dimensions. This reveals that all three dimensions of network effects apply to transaction platforms, empirically supporting the thesis of Cusumano et al. (2019) that transaction platforms tend to become hybrids over time.

Second, going beyond the industrial context, our study also brings forward the research stream on platform performance measurement (Floetgen et al. 2022). As traditional performance measurement and controlling concepts are mainly based on monetary metrics, Illich-Edlinger et al. (2021) extend the criticism raised by Melnyk et al. (2014), showing that financial metrics do not reflect important platform developments clearly enough. Given that existing research identifies the early phases of the platform lifecycle as the most difficult for platform organizations and conventional financial performance metrics provide too few indications of the individual value drivers of a network-based platform business model, we are confident that our KPI portfolio offers an improvement for platform organizations, especially in the early phase of the platform lifecycle. Hereby, the central challenge in identifying relevant nonmonetary indicators and indicator categories is to map the business model's cause-effect relationships reliably. Acknowledging that additional nonfinancial indicators are of significant importance for measuring performance in the context of digital platforms (Seiter and Autenrieth 2019; Floetgen et al. 2022), the 20 KPIs extend previously discovered platform control variables and metrics of platform ecosystem evolution, such as stickiness, platform synergy, or plasticity towards IIoT and network effects (Tiwana 2014; Seiter and Autenrieth 2019) and support future research on the platform performance measurement and establishment of performance measurement in platform organizations (Gomes et al. 2022). In particular, this supports industrial incumbents who are new to dealing with platform-based network effects (Marheine and Petrik 2021; Haki et al. 2022), as this managerial shift must be supported by developing suitable management tools (Horváth 2019; Gomes et al. 2022), with the KPI portfolio contributing here.

However, focus on network effect growth, the interactions between the platform users, or the condition of the platform ecosystem instead of traditional value drivers of linear business models requires a significant shift in management practices for platform-providing organizations. Platform managers are challenged to justify allocating budgets for micro-strategies or competitive actions (Ghazawneh and Henfridsson 2013; Eaton et al. 2015). This phenomenon is not emphasized by existing work on platform strategies or micro-strategies despite its criticality in the platform competition and according to our empirical data. The framework for platform management sheds light on how a balance between the three interdependent network effect dimensions for different market sides and the platform earnings can be supported. It thus addresses a challenge that occurs especially in firms with traditional controlling (McGrath 2020) or small and medium size platform companies without access to the capital market compared with platform giants in B2C. Hence, the framework complements the knowledge of the existing trade-offs in platform strategies (Karhu et al. 2020) and platform governance (Ghazawneh and Henfridsson 2013; Parker et al. 2017; Chen et al. 2021; Schreieck et al. 2022), highlighting two co-existing and contradictory necessities to stimulate growth and perform financially that need to be balanced by platform organizations.

Acknowledging this trade-off increases our understanding of the challenges of incumbent firms, who still manage their platforms with rules and control instruments developed for linear product business (Vial 2019). In conjunction with the KPIs, the proposed balanced view could help platform business units justify the measures aiming at network effects to the funders or internal financial controlling. Considering this challenge, the framework helps platform providers track their measures' success, especially in the competition for complementary engagement (Cennamo 2019). This helps achieve a more balanced value creation and appropriation management from the platform provider perspective (Chen et al. 2021). The structure of the KPI portfolio and the framework utilize the goals of a balanced scorecard, which has proven helpful as a management tool to measure the achievement of linked objectives and to prevent measures from being terminated prematurely (Kaplan and Norton 1996). Especially when incumbent firms decide to open a platform (Svahn et al. 2017; Schreieck et al. 2022), they may need a performance measurement system to justify this strategic decision before internal and external stakeholders. The portfolio can support the performance measurement of such decisions for managers and researchers, forming a foundation for future research on the individual determinants of platform openness or value for platform users in the context of IIoT.

Third, our paper offers several contributions at the intersection of the research streams on platform ecosystem strategies and governance (Jacobides et al. 2018; Tiwana 2014) and performance measurement (Floetgen et al. 2022), as the design of KPIs is an important building block for deriving adequate measures and evaluating their success (Tiwana 2014; Parmenter 2019). Prior research on platform strategies often uses past data to make sense of platform providers' competitive actions to establish their platform in the market (Karhu et al. 2018; Karhu and Ritala 2020; Cenamor 2021) and sustain in inter-platform competition (Stummer et al. 2018; Cennamo 2019). Since prior research on platform performance measurement only examines its antecedents (Floetgen et al. 2022), our study is among the first to provide a link between defining platform strategies and measuring the effectiveness of their execution (Micheli and Gupreet 2021). By providing 20 KPIs to measure how the network effects work, our work helps evaluate the organizational implementation of these strategies. The operationalization of the network effects is likely to help evaluate the effectiveness of governance measures (Svahn et al. 2017; Schreieck et al. 2022), capabilities (Haki et al. 2022), or micro-strategies (Eaton et al. 2015) aimed at network effect stimulation in the context of open platforms. Similarly, we posit that creating a performance measurement foundation for network externalities that can be used in future empirical studies to determine the effectiveness of ecosystem development activities is an important scientific implication of our study. Based on our results, researchers can further assess the effectiveness of organizational capabilities that aim to stimulate network effects and discover new critical success factors, while managers, especially in industrial incumbent companies, can better benchmark their platform decisions.

6.3 Limitations and conclusion

Our study, fundamentally rooted in a qualitative research design, encounters certain limitations. First, our research does not meet the requirements of statistical generalizability. It offers analytical generalizations, valid only for the conditions and specifics of the eight industrial platform provider cases recalled in the focus groups (Lee and Baskerville 2003). Although the participant numbers in each focus group and the sample may be considered small, the secrecy due to the competitive relevance of the research object and the resulting difficult access to data must be considered.

Our research approach with experts from industrial digital platforms might have resulted in neglecting potential interdependencies of network effects and their measurement options in other platform-mediated industries (Gawer 2020). Nevertheless, we attempted to mitigate this limitation by grounding our empirical results on theoretical findings from existing literature. However, further empirical studies are required to evaluate other possible dimensions of network effects that might be relevant in IIoT, such as the data network effects (Gregory et al. 2020).

A noteworthy limitation is that our empirical study only includes the platform provider perspective. Incorporating other perspectives (e.g., from end customers and complementors) could further improve the understanding of the developed network effect dimensions. Accordingly, we encourage other researchers to gather more empirical evidence on firms dealing with network effects, acknowledging the necessity to integrate strategic management and the management of network effects (Karhu et al. 2021). Additional data from other domains could furnish further evidence regarding a larger-scale applicability of the framework in practice and elaborate a more profound understanding of network effects management. Our study also does not consider the winner-takes-all outcome observed with network effects due to the non-dominant position of the firms involved in our workshops in the fragmented industrial platform market. Other overlooked network effect specifics include lock-in effects, which might vary between the network effect dimensions but are critical in an enterprise domain like IIoT. We also simplify the compatibility dimension and do not distinguish between vertical compatibility (i.e., machines, enterprise software) and horizontal compatibility (i.e., other platforms). established more general KPIs can also be further adapted specifically to IIoT. Lastly, while German firms have advanced in adapting the IIoT paradigm and input from an American platform provider was included, our findings do not necessarily apply to regions with differing economic systems (e.g., China).

To sustain intensive inter-platform rivalry, platform-providing organizations must develop effective strategies with network effects that are likely to play a decisive role. In this context, our study offers a multidimensional view on network effects to support the operationalization of this theoretical construct. Yet, to steer platform strategies and initiate appropriate actions, concrete KPIs for measuring network effects and their supporting measures are required (Micheli and Gupreet 2021; Floetgen et al. 2022). An empirically evaluated portfolio comprising 20 KPIs further supports this platform management objective. The portfolio's objective, if applied, is to enable performance measurement of digital industrial platforms. Including a financial perspective within the portfolio also aids in assessing the effectiveness of investments aimed at igniting network effects. Together with the framework, our findings generate a decision-making basis for managers to establish continuous performance management of digital industrial platforms recognized as vital in platform ecosystems and balance the responsibilities of organizations with financial constraints. In particular, the framework assists in revealing often untracked and underresearched financial aspects of platform ecosystem management (i.e., due to limited data accessibility).

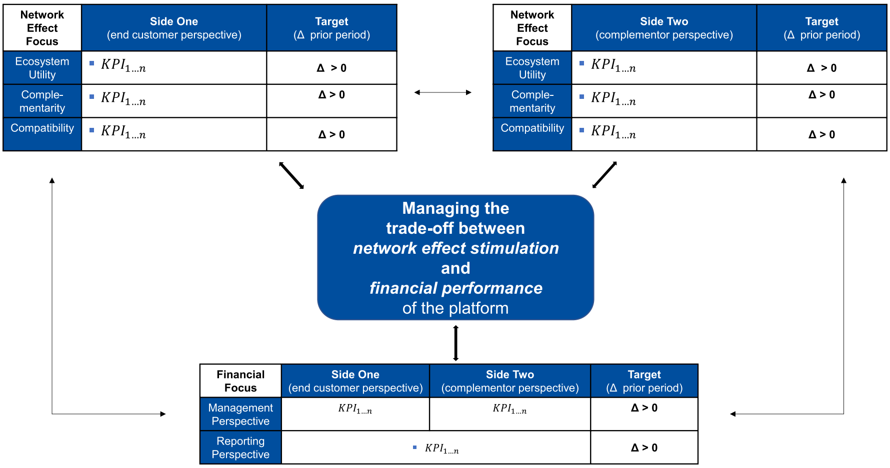
Contrarily, it is evident that a platform provider has to develop close relationships with platform users, encouraging them to share necessary data, a process often viewed critically due to coopetition amongst the ecosystem participants in B2B. Overcoming these acceptance barriers and cultivating respective capabilities (Vial 2019) can pose an organizational hurdle to measure network effects, thus indicating future research avenues. In addition, leveraging the developed KPIs, future research could develop new systematic approaches for benchmarking various digital platforms in IIoT and other domains.

Furthermore, the portfolio provides a foundation for elaborating new metrics and control systems for digital industrial platforms. As some experts revealed difficulties in measuring the network effects, the KPI descriptions also include some indications on collecting the necessary data for monitoring the KPIs. This opens door for future research on designing performance measurement IS that can cope with IIoT data. Also the fact that some of the KPIs possess a more generic nature can serve as an impetus for further research on domain-specific instantiations of network effect KPIs. Whilst this is a limitation, it broadens the applicability of the results beyond the context of digital industrial platforms.

However, the definition and continuous measurement of network effects across multiple market sides require interdepartmental cooperation. This can be prevented by certain organizational structures (Eggers and Park 2018). Additionally, dealing with the trade-off between financial performance and network effect measurement demands creative solutions from corporate accounting and managerial commitment. This finding underscores the complexity of internal business processes, which require greater adaptation for ecosystem establishment. These insights provide fruitful avenues for research on process management and the organizational structures of incumbent firms with a platform in their business structure (Vial 2019; Haki et al. 2022).

Lastly, the portfolio provides a grounding for future research on the differences in the logic of network effects in IIoT. Given the challenges platform providers face in generating and capturing value for themselves and other platform users, we hope our findings build the necessary antecedents for future discourses on platform strategies and network effect ignition.

Appendix A: Customizable template for balanced platform performance management



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Data availability The complete interview dataset is not publicly available in accordance with the terms agreed upon for data protection. However, in addition to the quotes available in the manuscript, the anonymized transcripts are available on request from the corresponding author.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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