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Abstract

To develop an innovation ecosystem and maintain a healthy ecosystem through contributions from partners, the ecosystem owner must balance exercising control over the partners and allowing them autonomy in their activities. While a large body of literature discusses the comparative statics of the optimal degree of "control" over "autonomy", few studies empirically investigate governance model dynamics during ecosystem development. This study sheds new light on this issue using information from the Siemens IoT Platform called MindSphere. Specifically, by measuring the similarity among the partners in terms of their business domain, we constructed an indicator of complementarity among platform participants. We then evaluate Siemens's platform governance strategy using Burt's constraint index (measuring structural holes in network data). Siemens changed its governance model from facilitating mutual complementarity among partners in the early stage of platform development to inducing more competition in its later stage using network externality as a centripetal force.

Keywords: platform, ecosystem, strategy, complementarity
JEL classification: O32, O36

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1. Introduction

The technology platform has emerged in a variety of high-tech industries, driven by information technology and scholars are paying growing attention to the management of platform ecosystems (Gawer and Cusumano, 2013; Evans and Gawer, 2015; van Alstyne et. al, 2016). The technology platform is organized by its owner, i.e., the “platform leader” (Gawer and Cusumano, 2002) or “keystone firm” (Iansiti and Levien, 2004), with multiple partners participating in the ecosystem. The delicate equilibrium between control and autonomy within partnerships emerges as a critical facet for the platform (ecosystem) owners (Wareham et. al, 2014; Parker and van Alstyne, 2018). The challenge lies in orchestrating an environment that encourages contributions from partners while maintaining a healthy and adaptive ecosystem. It is expected that partners will provide constructive investments under a condition of autonomy, while the platform owner should orchestrate and coordinate their activities for effective integrated service provision to the market. There is an inherent “paradox of change” or stability–evolvability tension, in ecosystem management (Wareham et. al, 2014).

Since the platform owner and partners share the profit from ecosystem output, private ecosystems exhibit an inherently competitive environment (Daymond et, al, 2023). The balance between control and autonomy has been investigated based on the microeconomics model, showing the comparative statics of the equilibrium point with regard to the competition between developers and the platform, the state of network effect, and the access rule to the platform (Parker et, al. 2017; Parker and van Alstyne, 2018). Empirically, Boudreau (2010) showed the concavity in the relationship between the openness of the platform and innovation performance in the case of the handheld computer industry. The existing literature extensively explores the static aspects of determining the optimal degree of "control" versus "autonomy." However, there is a notable scarcity of empirical studies that examine the dynamic governance models evolving during the lifecycle of an innovation ecosystem.

This study fills this gap by offering new insights into the dynamics of governance models in ecosystem development. In particular, we investigate the changes in ecosystem governance from the timing of its emergence through its growth. At the emerging stage of a private ecosystem, it is important to create conditions for cooperation, where partners cooperate and compete, centered around the owner’s core technological assets. However, competition across partners intensifies when the ecosystem grows and evolves due to the fundamental tension between value creation and capture. At this stage, the owner should create conditions for contained contestations to sustain the ecosystem dynamics (Daymond et. al, 2023).

We have shown such changes in the state of the ecosystem by looking into partners in MindSphere, the Industrial Internet of Things (IIoT) platform by Siemens. We examine partners' growth on the MindSphere platform from 2016 to 2019, focusing on complementary relationships across partners. To gauge the intricacies of the Siemens’ platform governance strategy, we use Burt’s constraint index—a metric designed to quantify structural holes in network data (Burt, 2005). Our analysis reveals a marked shift in the Siemens’ governance model, from fostering mutual complementarity among partners in the early stage of platform development to actively inducing more competition in its later stage.

This paper makes three contributions. First, by employing the wealth of information available from MindSphere partners, we empirically examine the dynamics of ecosystem governance, in contrast with the static analyses of the balance between control and autonomy that characterizes most of the past literature. Second, we provide a methodology for measuring complementarity among platform participants by assessing the similarity of their business domains. Third, we combine platform theory based on multisided networks and network externalities in the economics discipline (Parker and Alstyne, 2005; Raysman, 2009) and ecosystem theories centered around complementarity for value creation in management studies (Jacobides et. al, 2018) to explain the changing fundamental centripetal forces for ecosystem participants (Gawer, 2014).

The paper is organized as follows: First, we conduct a literature survey in both economics and management disciplines and present the hypotheses in the next section. Then, a description of MindSphere, focusing on its development of partners on the platform, is provided. The methodology for measuring complementarity based on business domain similarities is explained in section 4. The subsequent section is the empirical analysis, using of the Burt constraint index for network analysis on the degree of complementarity and descriptive regression analysis. We discuss the results of our empirical analysis in section 6 and conclude our paper with managerial implications and further work at the end.

2. Related literature and hypothesis

A "platform" indicates a shared functional space where multiple producers provide goods or services to multiple consumers (Gawer and Cusumano, 2013; van Alstyne et al., 2016). Platforms connect multiple producers and consumers by bundling various components on the producer side to provide integrated products and services to customers. For example, SAP brings together software companies that develop applications for its Enterprise Resource Planning (ERP) system (Ceccagnoli et al., 2002). An ERP system is core software that integrates various business administration functions, such as production, procurement, financial affairs, accounting, and human resources. However, multiple options are available depending on the industry and location of the customer firm. SAP does not develop each application independently but uses third-party contributions to the integrated software system. SAP provides third parties a System Development Kit (SDK) to create this producer-side ecosystem. Similar programs are also available from Microsoft (Azure Technology Partner) and IBM (IBM Cloud Business Partners).

Platform governance refers to a platform's rules, practices, and design to maintain a healthy ecosystem (a group of component producers and/or customers) on the producer side. The value of the ecosystem is determined by the diversity and dynamics of partners in the entire system (Iansiti and Levein, 2004). It is also important to cultivate generativity, i.e., the ability of partners to create, generate, or produce new outputs to integrate products and services (Wareham et. al, 2014). Therefore, a platform owner sets the rules and practices of producer-side ecosystem partners to induce their self-contained behavior.

The core system designs the platform and boundary resources that induce ecosystem partners' contributions to the whole system (Figure 1). Boundary resources work as an interface between the platform owner and partners in an arm's length relationship (Ghazawneh and Ola, 2013). SDK, a collection of software tools, libraries, and documentation, is a typical boundary resource. It includes software libraries, application programming interfaces (APIs) and integrated development environments including debuggers, simulators, and emulators. In addition to technical boundary resources, organizational approaches nurture partnership relationships, such as partnership programs, startup support programs, and hackathons (Dal Bianco et. al, 2014).

(Figure 1)

However, it should be noted that the platform owner and the partners may have some conflicts over the output-generated profit. A profit-sharing scheme that favors the partners is more likely to attract potential partners and induce their efforts on the ecosystem. In contrast, if the platform owner (or keystone player of an ecosystem) exploits too much profit from the system, it may deteriorate the ecosystem (Iansiti and Revein, 2004). Parker and van Alstyne (2018) formalized this trade-off using the IP policy for software developed by platform partners. The longer the duration of IP a partner can sustain, the more incentive the partner has to invest in this ecosystem. However, it is harmful from the viewpoint of developing a whole system because the platform owner and the other partners have less incentive to make complementary developments.

A certain level of control over partners' activities is required for quality control purposes. For example, a generous approach to partners' activities, the "let a thousand flowers bloom strategy," may lead to many poor quality output components that deteriorate the quality of all integrated services (Hagiu and Halaburda, 2010). Moreover, the diversity of partners' outputs is important because competition among competitors may damage their incentives to work together for complementary innovations. Therefore, a platform owner should be careful about the types of partners joining and leaving. This is particularly important for IoT platformers for business customers, who place more weight on the quality of the services compared with individual consumers in B2C platform services, such as smartphone applications.

Finally, the platform governance strategy differs by the stage of its development. Daymond et al. (2023) reviewed ecosystem management strategy papers to compare the design between the emerging and evolution phases. Compared to a public ecosystem without a leading firm, such as an entrepreneurship ecosystem, a private ecosystem with a platform leader competes with ecosystem players. An ecosystem emerges with transactional connections anchored by particular products and services. Therefore, a private architect of such an ecosystem should create conditions to facilitate both cooperation and competition among ecosystem players. However, a "contained contestation strategy" is recommended for ecosystem evolution because competitive tensions intensify among already-connected ecosystem players in this phase.

In the early stage of platform ecosystem development, the centripetal force associated with complementary networks is weak. Therefore, its owner should make substantial efforts to design a complementary network of partners and facilitate transactions among them. To promote the use of its boundary resources, the access policy should be generous, such as free access to APIs. The owner should also be careful to select potential partners that ensure the quality of outputs for better customer relationships; that is, the gate of ecosystem participation should be controlled or started with only "invited" partners.

H1: In the early stage of ecosystem development, the platform owner invites partners with strong complementarity with the entire ecosystem, and the degree of complementarity decreases as the ecosystem grows in size.

Ecosystem complementarity emerges from the cospecialized investments made by its participants (Baldwin, 2020). Cospecialization can be found both between the platform owner (or "keystone") and its partners ("niches") (Iansiti and Levien, 2004) and between any two partners. Given that such investment is nongeneric in nature, the longer a partner stays in the ecosystem, the more likely she is to invest in relation-specific assets with the ecosystem. Therefore, the degree of complementarity with the ecosystem should be stronger for long-time partners than for new ones. However, newcomers prefer to join ecosystems that do not incur substantial nongeneric investments to avoid the risk of a potential holdup problem. Therefore,

H2: The degree of complementarity is stronger for long-term partners and weaker for newcomers.

As the ecosystem develops and evolves with more customers, it becomes more important for the platform owner to manage a two-sided network effect across the producer and consumer sides (Parker and van Alstyne, 2005). This indirect network effect emerges in the interactions between producer-side diversity in service provision and consumers (potential) on the market side. Therefore, the platform owner opens access to the platform ecosystem for potential partners and encourages collective generativity through partner investment in complementary innovations (Wareham et. al, 2014). When the indirect network effect kicks in, the potential profit from the ecosystem becomes large enough for newcomers to mitigate the risk of the holdup problem with relation-specific investments on the platform. Therefore,

H3. The difference in the degree of complementarity between existing and new partners becomes smaller as the ecosystem grows.

3. Siemens MindSphere: Development of the IoT ecosystem

We use the case of MindSphere, the IIoT platform developed by Siemens, to further analyze the dynamics of platform governance strategy. Siemens is a multinational technology company focusing on the energy, infrastructure, transport, and healthcare industries. It is Europe's largest industrial manufacturing company and the global industrial automation and software market leader. Over the past years, MindSphere has achieved a leading global position in IIoT as a facility and service solution across various sectors (Annanth et. al, 2021).

Siemens launched MindSphere 1.0 in early 2016. The platform was initially introduced in a beta release with plans for continuous development. MindSphere was built as an open ecosystem intended for industrial enterprises to use as a foundation for their digital services. At this stage, Siemens had mostly established partnerships with business consulting firms and resellers to promote the platform. In addition, in this phase, Siemens established a partnership with the Cloud Foundry Foundation to integrate Cloud Foundry into its platform, which is an open source, multicloud application platform (PaaS) (Pertik and Herzwurm, 2019). MindSphere provides support for Cloud Foundry, enabling developers to leverage its functionalities. Cloud Foundry, an open-source platform as a service, offers best practices for cloud-based software development, simplifying complexity and providing services for application delivery and management. Cloud Foundry allows developers to deploy and scale their applications without being tied to a specific cloud vendor. This flexibility reduces costs and development efforts and expands the platform's reach by facilitating compatibility between MindSphere and other platforms supported by Cloud Foundry.

Siemens launched MindSphere 2.0 in August 2017 and continued until the end of 2017, with partnership development with new consulting companies continuing throughout (Pertik and Herzwurm, 2019). Even though this is a short-lived period, some important events occur during this stage. A strategic partnership with Amazon has been established to provide MindSphere on the AWS Cloud (Annath et. al, 2021) and one with Software AG. Collaboration with software companies such as Software AG allows Siemens to incorporate a device management module into MindSphere, enhancing the platform's capabilities for managing and controlling IoT devices. Finally, in December 2017, Siemens announced its Official Partner Program.

Through the MindSphere Partner Program, partners can create IoT applications and solutions on the MindSphere operating system. This program is tailored to support partners aiming to harness the open cloud-based essence of MindSphere. It offers various options, including connectivity protocols for devices and enterprise applications, industry-specific applications, advanced analytics, and a development environment that combines Siemens' open platform as a service (PaaS) functionalities with native Amazon (AWS) cloud services. The MindSphere Partner Program employs a universally standardized three-tier framework (Platinum, Gold, and Silver). Partners across all tiers can access fresh business development advantages and earn influencer fees by identifying and assisting in finalizing new MindSphere opportunities using a deal registration tool. Gold and Platinum Partners also qualify for business development funding to propel proof of concept, marketing, and technical endeavors. A designated MindSphere partner manager collaborates with these partners to develop a shared business plan that aligns resources for mutual achievement.

At the beginning of 2018, Siemens launched MindSphere 3.0, the more mature version of the platform. In this stage, the number of partners and platform activities have lifted off the ground and increased significantly. A couple of strategic partnerships have been established in this phase (Pertik and Herzwurm, 2019). Siemens, at the forefront of automation and digitalization innovation, and HP, a pioneer in industrial 3D printing, established a partnership to broaden their collaborative additive manufacturing solution using the MindSphere digital twin of product, production, and performance. Strategic partnerships with Rittal and Atos were also established in this phase to develop edge data centers (Pertik and Herzwurm, 2019) and a strategic partnership was announced with the car manufacturer Volkswagen, connecting 122 factories to the cloud. Volkswagen and Siemens also aim to create new functionalities and services for the Industrial Cloud in the future. They plan to collaborate with machine and plant suppliers to make these offerings accessible to all prospective partners.

Finally, at the beginning of MindSphere 3.0, Siemens AG and 18 partner companies established the "MindSphere World User Organization," which is dedicated to advancing the cloud-based, open MindSphere IoT operating system. The primary goal of this organization is to expand the global presence of the MindSphere ecosystem. It aims to support individual members in developing and optimizing IoT solutions on the MindSphere platform, enabling them to enter new markets within the digital economy. Furthermore, the association is vital in offering suggestions for enhancing the MindSphere IoT operating system based on specific requirements. It also promotes fair and equitable use of data by recommending strategies that create a level playing field. In addition, the organization intends to leverage the power of MindSphere to drive advancements in science, research, and teaching, fostering innovation and knowledge exchange in these domains.

Another purpose of establishing the MindSphere World organization is to develop standards, which are crucial for the success of the platform ecosystem over its rivals. "The development of standards plays a decisive role in establishing a global ecosystem. Therefore, MindSphere World members are compiling joint recommendations on standards for MindSphere-based applications. We are also developing suggestions to enable interoperability between different MindSphere-based solutions", said Andreas Oroszi, board member of "MindSphere World" and Senior Vice President Digital Business at Festo.[1] The user organization initially consisted of machine tool companies and automation providers. However, by November 2018, the organization had welcomed new members with diverse specializations, including software development firms, system integrators, financial institutions, industrial wholesalers, and universities. At the same time, a range of software development and data analysis companies became part of the partner program. Many of the companies have double membership in both the Official Partner Program and User Organization; therefore, both types of partners are treated equally in our analysis (Pertik and Herzwurm, 2019).

4. Measuring complementarity across ecosystem partners

An ecosystem is a group of organizations with nongeneric complementary relationships without hierarchical control of one member. Its organization is between the hierarchical structure of the supply chain (pipeline) and transactions in the market (Jacobides et, al, 2018). Nongeneric refers to the relationship specificity across organizations within an ecosystem. For example, a mobile app for iOS works for Apple’s iPhone, but not for Android smartphones, and the value of the iPhone increases with the number of apps on its platform. Therefore, the relationship between app providers and Apple is one of nongeneric complementarity. Conversely, the iPhone and sim card complement each other (without a sim card, the iPhone cannot be used as a mobile phone), while the relationship is generic, in the sense that both products can be purchased separately in the market. Therefore, this relationship is characterized as generic complementarity, and it is a market transaction, instead of an ecosystem.

The relationship between an assembler and its parts in the automotive industry shows nongeneric complementarity, but the assembler fully controls the specifications of the parts. Adner (2017) proposes that “the ecosystem is defined by the alignment structure of the multilateral set of partners” and that the alignment involves mutual interactions, but it allows

[1] D. Petry, "FOUNDING OF THE MINDSPHERE GLOBAL USER ORGANIZATION FOR OPEN IOT PLATFORMS," Siemens AG, 2018. [Online]. Available: https://ffg-ea.com/en/companies/press/detail/founding-of-the-mindmphere-global-user-organization-for-open-iot-platforms/

some room for the discretion of both parties, instead of either party fully controlling the others' product specifications. In this sense, when the supplier provides the parts designed by the assembler, it is a supply chain relationship or "pipeline", instead of an ecosystem.

The product architecture of an output product/service determines an optimal style of organization, ecosystem, market, or pipeline. Because the interface of a sim card to a smartphone is standardized, these two can be traded in the market, i.e., based on modular architecture. In contrast, the relationship between automotive parts is characterized as "integral", where the specifications of each product are interdependent. The smartphone app ecosystem is not completely modular or integral, i.e., supermodular structure (Milgrom and Roberts, 1990). In modular architecture, the sum of the value of each component is equal to the value of its combination, i.e., V(A) + V(B) = V(AB). However, super modularity leads to the relationship of V(A) + V(B) < V(AB). It would be characterized as a weak complementarity because the integral architecture leads to the relationship of V(A) + V(B) < < V(AB), or the value of each component (V(A) or V(B)) is almost 0 (strong complementarity) (Baldwin, 2020).

Jacobides et al. (2018) posited that there are two types of complementarity in the ecosystem: consumption complementarity, referring to V(A) + V(B) < V(AB) on the consumer side, and production complementarity, referring to coordinated investment in A and B, which gives higher returns (or smaller cost) than the sum of individual investments. In the case of IIoTs, hardware and software integration is important to activate a Cyber Physical System. For example, the digital twin makes the product development process faster and more efficient by using computer simulation models based on real data from physical experiments. The variety of sensors and machines integrated into the IIoT platform improves the digital twin system's prediction performance, improving consumer utility. At the same time, an advanced analytical model based on AI technologies by a third party could be developed more efficiently using the SDK provided by the platform owner. Therefore, complementarity in production could also emerge from the various software developers.

The degree of complementarity varies by the pairs of components, and it should be evaluated by either market or the production technology experts (Shipilov and Gawer, 2020). However, there is a general relationship between the degree of complementarity and the similarity of the two components (Table 1). Regarding production complementarity, the greater the similarity of the components, the more complementarity can emerge. This is because similar components are expected to share more common resources, which could be invested jointly to reduce total costs. As for consumption complementarity, the more similar the components, the less complementarity can emerge, since such a combination cannot a variety of services.

If the total value of the ecosystem, or the integration of two parts, is simply the sum of the two sides, there is no clear relationship with the similarity. However, it should be noted that the marginal value of the ecosystem (as compared to the sum of values by separate provisions) is not simply equal to the sum of value added (V(AB)>V(A)+V(B)) on both sides because an indirect network effect across consumer and producer sides could make the value of one side more variable (Parker and van Alstyne, 2005; Motohashi, 2021). In the example of the digital twin, the variety of sensors and machines attracts more customers to the platform, inducing more partners to join this ecosystem. Similarly, the more data analytic vendors join the ecosystem, attracted by complementarity in production, the better overall system performance, inviting more customers.

(Table 1)

5. Empirical analysis of network complementarity among MindSphere partners

In this section provides the network analysis among MindSphere partners based on the methodology of measuring complementary products and services. We used the dataset in Petrik and Herzwurm (2009), which shows the names and dates of entry in the Siemens platform ecosystem of 235 partners. There are eight timings for entry from May 24, 2016 to May 13, 2019 (until the observation period of June 26, 2019), as follows.

(Table 2)

It is linked with the information of the firm's activity (textual description) in Crunchbase. We used word2vec embedding with 300 dimensions to represent the activities of each partner. First, we conduct clustering analysis to understand the content of partners' activities. The k-means methodology identifies six clusters: "Machinery", "IT infrastructure", "Consumer electronics", "Industrial automation", "Data Analytics", and "University" (see the Appendix for details of clustering analysis).

The sample is split into two parts: one in the early stage (115 partners joining before July 2018) and the other in the late stage (129 partners joining after July 2018), to see the difference in their types of activities. Machinery and data analytics firms joined the platform ecosystem in the early stage, while the shares of IT infrastructures and industrial automation are larger in the later stage. The ecosystem grew by first enriching the components of IIoT solutions (hardware and software components). Then, more firms related to improving service quality (such as integrated industrial automation, cyber security, and cloud service solutions) joined MindSphere to strengthen its market presence.

(Figure 2)

Next, we investigated how the state of the complementarity network of the platform ecosystem changes over time by examining the degree of complementarity across its partners. Specifically, we constructed a complementarity matrix estimated from the pairwise similarity across all 235 partners. As shown in the previous section, if two components are not very similar or not very different, they are probably in a complementary relationship. Therefore, once we set the upper and lower bounds of the activity similarity measure of the partners, it is possible to identify if they are in a complementary relationship.

We calculated the pairwise cosine similarity of embedding vectors for the 235 pairs of partners and set the upper threshold value to 0.5 and the lower value to 0.15. Table 3 shows the mean pairwise cosine similarities within and between any of the six clusters. We would expect most of the partners across clusters (such as machine and IT infrastructure) to be in a complementary relationship; however, in the case of consumer electronics and university partners, the substance may be too far from the other four types of partners. If few common resources are to be jointly invested, complementarity in production is likely small (see Table 1). As shown in Table 3, most of the mean similarities between consumer electronics and university partners is greater than 0.5 (shared cells). Therefore, we use 0.5 as the upper threshold value. Regarding the lower threshold value, it should be noted that the smallest within-cluster mean similarity is 0.193 (for IT infrastructure cluster). Given the heterogeneity of partners even within the same cluster (such as type of activities, location of market etc.), the lower threshold value should be lower than 0.193. We checked the distribution of pairwise similarities and found that the lowest 25% (first quartile) is around 0.15; therefore, we use this value as the lower threshold value. Finally, the pairwise similarity matrix (235*235) can be converted to the pairwise complementarity matrix by setting 1 (complementary relationship) if the similarity score is higher than 0.15 and lower than 0.5, and 0 (not complementary relationship) otherwise.

(Table 3)

To evaluate the degree of complementarity among MindSphere partners, we use the constraint index based on the complementary matrix obtained above. The constraint index identifies the structural holes in social networks, reflecting the extent to which each node is interconnected with others, using the following formula (Burt, 2005).

$$C_i = \sum_{j \in V_{i,j!=i}} (p_{ij} + \sum_{q \in V_{ij,q!=i\ or\ j}} p_{iq}p_{qj})^2$$

$$p_{ij} = \frac{a_{ij}}{\sum_{k \in V_i, k!=i} a_{ik}}$$

where Burt's measure of constraint, Ci, of node "i" is calculated by Pij, the proportional tie strength between nodes "i" and "j", obtained by the elements (aij) of adjacency matrix A and vertex of i's ego network, Vi. Here, we use a complementary matrix for A, an undirected network with an element of 0 or 1, and Pij can be simplified as follows:

$$P_{ij} = \frac{1}{degree\ centrality\ "i"}\ if\ a_{ij} = 1, otherwise\ 0$$

Ci is high if partner "i" is in a complementary relationship with a small number of other partners (small degree centrality), and more partners have complementary relationships with both partner "i" and its complementary partner. The higher the constraint measure, the more likely the activities of partner "i" depend on the other partners. In other words, a partner with a high constraint measure is located in a position of strong complementarity in the ecosystem.[2]

The constraint measures are calculated for each partner by the entry timing to the MindSphere ecosystem. As shown in Table 2, there are eight times of partnership entries in our dataset, starting May 25, 2016. Firms that entered the ecosystem on May 25, 2016 (20 firms) are called the 1st cohort, then the average of constraint measures by time and cohort (until the 8th cohort, the last batch on May 13, 2019) is shown in Figure 3. It is shown that the constraint measure decreases over time, indicating that the degree of complementarity becomes weaker as the ecosystem grows.

(Figure 3)

To test the hypotheses in section 2, a descriptive regression is conducted on the constraint measure, based on the panel dataset with 325 samples over eight timings. To set the dummy variable EARLY, we split the entire period into two, until October 13, 2018 and after. In addition, the dummy for new entrants at each time is NEW. The results are shown in Table 4. From model (1) to model (3), the dependent variable is constraint measure C. For the rest of the regression models, the first component of C, that is $\sum_{j \in V_{i,j!=i}} (p_{ij})^2$, reflecting only the direct complementary relationship of the partner "i", is used as a dependent variable. For all models, the cluster type (six clusters) is controlled.

(Table 4)

First, positive and statistically significant coefficients are found for EARLY in models (1) and (2), indicating that the constraint measure declines as the ecosystem grows. The coefficients of the first component of the constraint measure are positive, but not statistically significant in model (6). Therefore, the decline in the degree of complementarity is attributed to structural changes in the network, instead of changes in direct complementarity in the ego network. These findings are consistent with Hypothesis 3.

Second, positive and statistically significant coefficients are found for NEW in models (1) and (4), but this is not the case after controlling for NEW. Taken together, positive and statistically

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[2] Such a node is positioned with a smaller structural hole to make independent actions in a social network.

significant coefficients of EARLY*NEW indicate that the positive relationship is found only in the early stage of ecosystem development. Therefore, Hypothesis 2 is partially supported. However, it should be noted that these findings are consistent with Hypothesis 3, that the difference between existing partners and newcomers decreases as the ecosystem grows. When the ecosystem becomes sufficiently large, the entry decision by newcomers is mainly driven by the network effect, as compared to the cost of relation-specific investments.

6. Discussion

In the ecosystem development process, Siemens invited consulting firms such as Accenture, PWC, McKinsey, and system resellers to promote the MindSphere 1.0 platform. In addition, Siemens integrated Cloud Foundry, an open-source software as a service, into the platform. The major development in MindSphere 2.0 is its partnership with Amazon Web Services to improve user accessibility to the platform. In these early periods, Siemens controlled access to the ecosystem completely.

In December 2017, Siemens announced the MindSphere Partner Program, which allows a partner to create IoT applications on the platform. In this sense, the EARLY dummy in the regression model, until October 13, 2018 or after, distinguishes early-stage partners with voluntary participation from the latecomers in the organic growth process of the ecosystem. Siemens extended its international partner network by forming “MindSphere World User Organization” in early 2018. Therefore, the decrease in the degree of complementarity in the network can be interpreted with the diversity of partner types and its geographical scope.

From a partner's viewpoint, it is important to evaluate the cost and benefit of joining the ecosystem. On the cost side, given that the ecosystem expects nongeneric complementarity among components, a potential partner should make some relation-specific investments. Even though the degree of holdup risk in the case of supermodularity is not as large as that in the case of integral architecture, a partner joining in the ecosystem has to consider some risk ex-ante.

On the benefit side, a part of the value added generated by coordination (V(AB) V(A) V(B)) is expected. This marginal benefit is proportional to the degree of complementarity; therefore, examining potential complementarity by joining the ecosystem is important. Since a newcomer to the ecosystem is more careful in evaluating its fitness to the ecosystem than existing partners, the positive and statistically significant coefficients are found to be NEW dummy variables in our regression results. However, as the ecosystem grows, the network effect becomes more of an important factor to consider. Hence, the statistically significant difference between newcomers and existing partners disappears in the later stage of our sample.

Note that the coefficients of EARLY to measure constraints are statistically significant, whereas that of the first term of C is not so, after controlling for NEW (model (3) and (6)). The first term of the constraint measure, i.e., the direct complementary relationship with other partners, is observable to each of the partners, while it is difficult to know the degree of complementarity of the entire network. Therefore, our regression results indicate that an observable degree of complementarity (first term) to partners does not change over time, while an unobservable degree coming from the whole network structure decreases. This could be interpreted as the centripetal power of the ecosystem shifting from one of complementarity to network externality as the size and diversity of the ecosystem network increases. The power of network externality could outweigh the strong complementarity incurred from an integrated architecture system (V(AB) > > V(A)-V(B)), so that the open platform strategy always outperforms closed vertically integrated systems in the case of a strong indirect network externality available (van Alstyne et. al, 2016; Parker et. al, 2017).

When a network effect kicks in, the platform owner can begin to appropriate its rent from the ecosystem. The MindSphere’s official partnership program has a three-tier structure (Platinum, Gold, and Silver), with a stratified service and fee schedule. The higher the level of partnership, the more services the platform provides at a higher price. Charging fees for accessing the platform contributes to the quality control of the partner's outputs (Hagiu and Halaburda, 2010), and the layered scheme facilitates self-selection for partners' involvement, depending on the level of their motivation to contribute to the ecosystem.

7. Conclusion

This study sheds new light on the dynamics of ecosystem governance using information from MindSphere, the Siemens IIoT platform. By measuring partner similarity in terms of their business domain, we constructed an indicator of complementarity among platform participants. Then, the network structure is analyzed using Burt's constraint index (measuring structural holes in network data), together with a descriptive regression analysis to find some regularities in the distribution of the constraint index by partners and times. The constraint index decreases over time, suggesting that network complementarity also decreases over time. In addition, newcomers to the ecosystem are attracted by its fit to the whole network regarding complementarity with their business activities, particularly at the early stage of ecosystem development. However, as the partnership network grows, the difference between newcomers and existing partners disappears, suggesting that the network externality becomes a more important force in attracting newcomers into the ecosystem.

Many economics studies view ecosystem governance as a trade-off between control and autonomy (Parker and van Alstyne, 2018). However, our case study shows more nuanced findings in real-world phenomena. In the early stage of ecosystem development, Siemens controlled the type of partners to join the ecosystem, while facilitating open access to its boundary resources, such as Cloud Foundry, an open-source multicloud application PaaS. Siemens controlled the type of activities but provided an autonomous access policy on its boundary resources. In the later stage, after Siemens started the official partnership program, MindSphere was open to potential partners but with pricing to enable them to access boundary resources, such as software toolkits. Therefore, ecosystem governance should be framed not with the trade-off between control or autonomy but with the dualism of control and autonomy. Similar to the concept of ambidexterity, exploration, and exploitation should be simultaneously dealt with using a variety of management levers (Wareham et. al, 2014).

One of the implications of our analysis is that ecosystem governance should be consistent with the centripetal force or partner's incentives for participation, depending on the stage of ecosystem development. In the emerging stage, the main force is the complementarity expected from joining the ecosystem. In this phase, the platform owner carefully designs the scope of the ecosystem and invests in the technologies, enhancing the complementarity for potential partners. Siemens has invested in the IT infrastructure, such as an open-source PaaS system and a partnership with Amazon Web Service (MindSphere 1.0 and 2.0). In MindSphere 3.0, Siemens initiated an official partnership program to open its ecosystem to various complementers. As the system grows, it is important to manage healthy ecosystem development through quality control of the entire system. The major centripetal force at this stage is network externality, incurred by the indirect network effect across producers and consumers. However, inappropriate quality control of partners could degrade customer trust, which leads to a loss of indirect network effects (Hagiu and Halaburda, 2010).

Another implication related to this point is that network size does not always lead to greater network effects. While size does matter for the network effect in the ecosystem, its quality is equally important. Both the size of the ecosystem (producer side) and of the customer is necessary to promote the indirect network effect. Unless the platform owner orchestrates the partners' activities to meet customer needs, initiating the positive feedback loop of the indirect network effect is impossible. Partnership management and the platform owners' data analytics capability is important to creating user value through AI and data network effects (Gregory et. al, 2021).

Although this paper proposes a new methodology for analyzing a complementary network of ecosystem partners based on extensive use of secondary datasets, some limitations remain.

First, a qualitative assessment by experts is necessary to evaluate the degree of complementarity (Shipilov and Gawer, 2020). Our methodology, based on the similarity of partners' business domains, is only roughly validated by clustering analysis; however, it does not go through a formal evaluation by examining the details of each partner's resources.

We also acknowledge limitations on the generalizability of our findings. This study is based on a case study of the Siemens IIoT platform, and our approach assumes that MindSphere is a successful case of ecosystem governance. It should also be noted that our case is based on a technology platform for B2B business, with quite heterogeneous customer needs. The stage of network externality is different between B2B and B2C platforms, such as smartphone platforms (iOS and Android) (Motohashi, 2021). Therefore, the area to which the implications of our study should be applied should be carefully examined.

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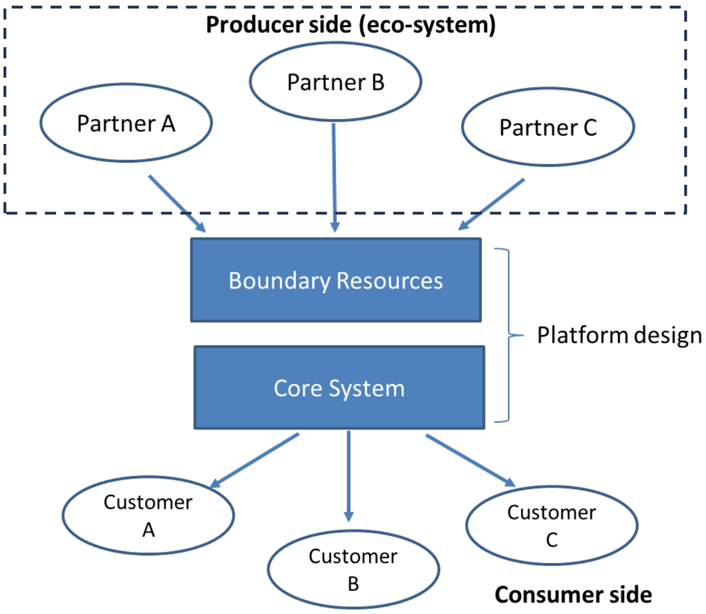


Figure 1: Structure of platform with producer ecosystem

Components similarity	Low	medium	Low
Complementarity in Consumption V(C)	Low	medium	High
Complementarity in Production V(P)	High	medium	Low
Total value of combination V(C,P)(>V(C)+V(P))	Medium	high	medium

Table 1: Components similarity and value of ecosystem

Date of entry	# of partners	Version
5/24/2016	18	MindSphere 1.0
7/24/2017	14	MindSphere 1.0
12/5/2017	44	MindSphere 2.0
6/20/2018	39	MindSphere 3.0
10/13/2018	25	MindSphere 3.0
12/1/2018	38	MindSphere 3.0
2/18/2019	28	MindSphere 3.0
5/13/2019	29	MindSphere 3.0

Table 2: Siemens MindSphere ecosystem development

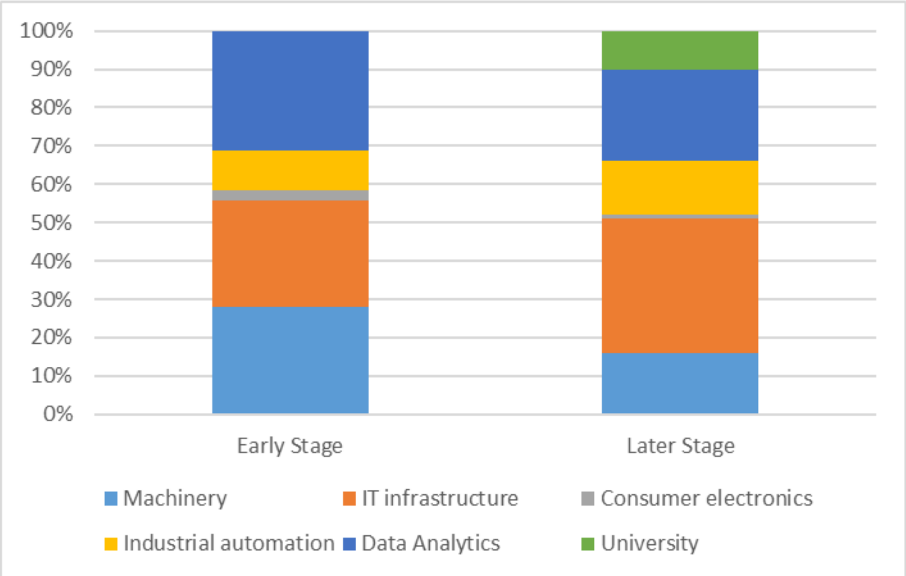


Figure 2: The share of partner counts by entry timing and type

	MA	INFRA	CE	IA	Analytics	Univ
Machinery	0.370	0.298	0.503	0.328	0.353	0.529
IT infrastructure		0.193	0.436	0.233	0.262	0.465
Consumer electronics			0.625	0.445	0.483	0.639
Industrial automation				0.250	0.299	0.490
Data Analytics					0.322	0.505
University						0.568

Table 3: Mean cosine similarity within and between clusters

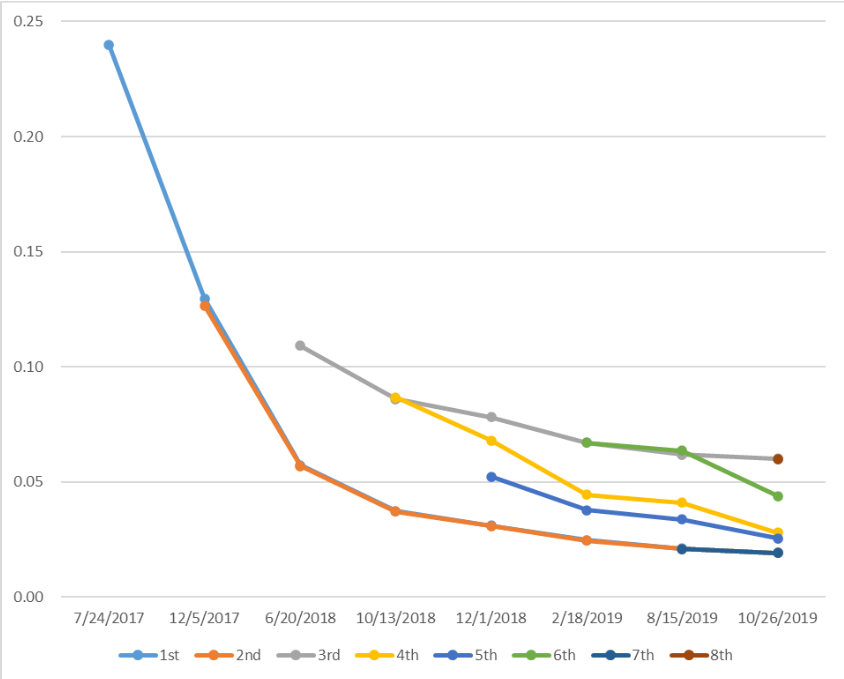


Figure 3: Constraint measures of MindSphere partners by cohort

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable	C	C	C	First part	First part	First part
EARLY	0.0312***		0.0183**	0.0177**		0.0112
	(0.01)		(0.01)	(0.01)		(0.01)
NEW		0.0307***	-0.0031		0.0150*	-0.00164
		(0.01)	(0.01)		(0.01)	(0.01)
EARLY*NEW			0.0750***			0.0379**
			(0.02)			(0.02)
Constant	0.264***	0.242***	0.266***	0.183***	0.172***	0.184***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Cluster Dummy	YES	YES	YES	YES	YES	YES
Observations	997	997	997	997	997	997
R-squared	0.156	0.154	0.191	0.143	0.142	0.153

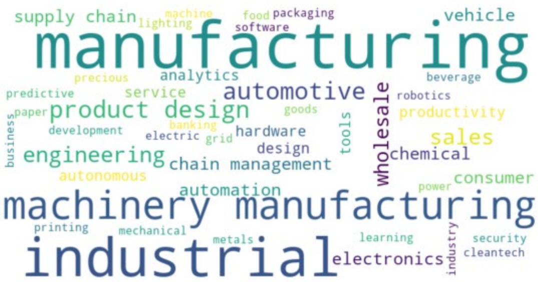
Standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 4: Descriptive Regression Results

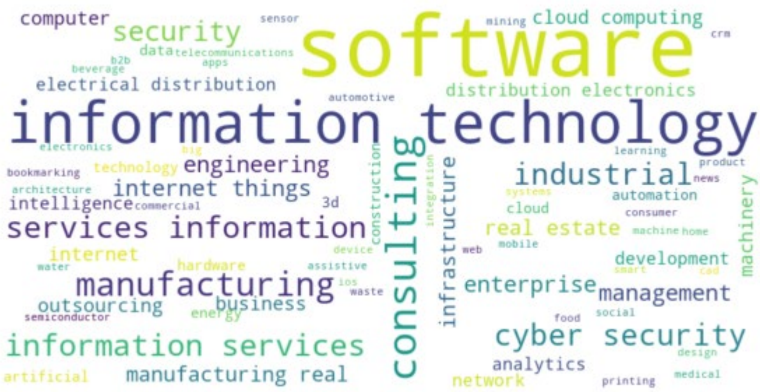
Appendix: Clustering analysis of partner's business domain

We have conducted k-means clustering, based on the TF-IDF weighted word vector for each of 253 partner business descriptions, with 4, 5, 6, 7 and 8 clusters. Then, we check the distribution of pair-wide cosine similarity, for both "within" cluster and "between" clusters. In general, the cosine similarities within cluster should be higher than that between cluster. However, due to the substantial heterogeneity in the business description of partners, there is a substantial confusion across these two types of cosine similarity, which cannot be separated clearly. We compare the distributions of cosine similarity between two types (within and between), together with word cloud results in each number of cluster, and decided to use the results with 6 clusters. The followings are the word cloud results in case of 6 clusters for labeling each cluster.

Cluster 1: Machinery

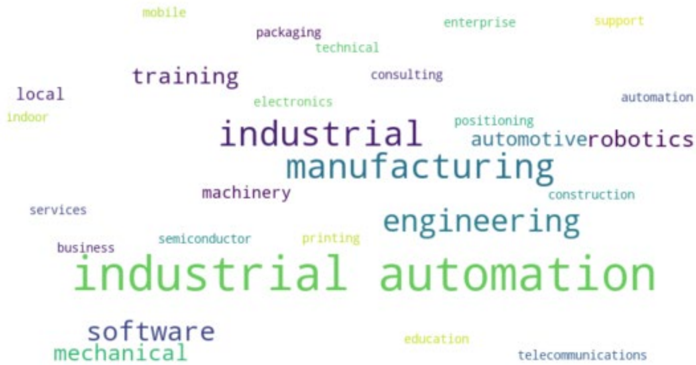


Cluster 2: IT infrastructure



Cluster 3: Consumer electronics

Cluster 4: Industrial automation



Cluster 5: Data Analytics

Cluster 6: University