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Structural Holes in the Multi-Sided Market: A Market Allocation Structure Analysis of China's Car-Hailing Platform in the Context of Open Innovation

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Abstract: Car-hailing platform governance is an emerging topic of research and practice. The governance of the data-driven platform economy is challenging the research paradigm of competition regulation in the context of open innovation. This research is trying to reveal the market allocation structure of China's online car-hailing industry from the perspective of personal data allocation by the study of Application Programming Interface (API) of sample platforms. On the basis of the networked nature of personal data allocation via APIs, this research constructs a mathematical model of the edge weight of data resource connections between platforms. Furthermore, this research optimises the structural hole analysis of complex networks to discuss the state of personal data resource allocation in China's car-hailing industry. Results reveal that there are obvious structural holes within the sample network. When compared with related indicators, we found that accessing personal data resources is an essential component of the sample network competition capability and sustainable innovation. Social media platforms and online payment platforms more greatly impact car-hailing platform competition than other types of platforms within the multi-sided market context. This research offers a research perspective of personal data allocation for further study of competition, regulation and sustainable innovation of data-driven platform economies.

Keywords: multi-sided market; market allocation; competition; structural hole; platform economy; sustainable innovation; open innovation

1. Introduction

Globally, online car-hailing (also named as ride-hailing) services have gradually become recognised and accepted in society, becoming an essential method of urban ground traffic. Thus, they are an important component of both platform and sharing economies [1]. Uber and Lyft (U.S. car-hailing companies) are globalising fast, and China has responded. In 2012, DiDi Chuxing and Kuaidi Dache

began offering online taxi-hailing services, marking the beginning of the Chinese domestic online car-hailing industry. In 2014, Tencent Inc. and Alibaba Inc., known as China's tech-giants, joined the car-hailing industry. Soon after, other online car-hailing platforms, such as Dida Dache and 51 Yongche emerged. Competition in the online car-hailing market has since become fiercer. In a segmented market, new online car-hailing platforms continue to emerge, and a new round of global market competition has neared.

Online car-hailing platform governance is now a hot topic of study of platform economy, and its multi-sided market attracts much attention. First, online car-hailing platforms utilise massive personal data from customers within the multi-sided market to greatly improve market distribution efficiency [2]. Second, customers' personal data have been abused on these platforms for the purpose of manipulating market-resource allocation via algorithm-supported discrimination. The market power abuse issue, based on massive data resources and high efficiency algorithms (e.g., Google and Facebook), has become a serious governance issue in Europe [3]. In the domain of policy research of platform economy, governance "refers to the apparent spread of markets and networks following these reforms (of the public sector). It points to the varied ways in which the informal authority of markets and networks constitutes, supplements, and supplants the formal authority of government." [4]. The rapid development of the platform economy has been accompanied by increasingly negative issues that harm society's welfare. For example, Facebook's privacy leaks have caused serious damage to various political campaigns [5]. The study of data resource governance of online platform is becoming a fundamental challenge for the sustainable innovation for the future economy [6].

The platform economy significantly differs from traditional economic models in terms of resource allocation and market structure [7,8]. According to recent research of Australian Competition and Consumer Committee (ACCC), platform economy generates more marketing, competition and innovation efforts by aggregating massive terminal user's social media personal data resource. In the ACCC's report, personal data resource is defined as the anonymised data that cannot trace the identified information of the terminal/individual user. The economics of personal data resource includes the commercial transaction, transmission and application [2]. Massive personal data resources are transferred and allocated that are presented as a network structure via the online platform Application Programming Interfaces (APIs) [9]. API is becoming a critical economic component of platform economy in the innovative context of openness. Each aspect of the online platform contains the complete consumer markets of different types of personal data resources from terminal users [10,11]. Platforms with greater market power are offering Open API for multiple stakeholders in a multi-sided market in the context of open innovation [12]. For instance, Facebook and Google build up API documents for individual and industrial users to access data resource for developing more application scenarios [13,14].

In terms of regulation theory from the perspective of governance research, the critical purpose of governance or regulation of industry is optimizing the structure of resources allocation to avoid the risks of monopoly that reduces the dynamics of sustainable innovation [4]. Hence, the analysis of the structure of resources allocation is the essential procedure of the discussion of industry governance. Data governance is the emerging issue of the platform governance, since massive data, including the large scale of personal data, have become the essential resource of the platform competition. The improvement of the efficient of data usability is the critical issue of platform governance and regulation. Consequently, for the purpose of sustainable innovation of the platform economy, the discussion of the market allocation will improve the understanding of the mechanism of the personal data resource as the emerging industrial resource. Nevertheless, there has been little research on the platform resource allocation structure from the perspective of personal data as an economic resource in the multi-sided market context. According to the research of Organization for Economic Co-operation and Development (OECD), resource allocation mechanisms and competition structures of multi-sided markets remain difficult to effectively measure and verify. The traditional antitrust

method is limited by comprehensive understanding of the nature of platform economy. Furthermore, there are still fewer empirical studies with the perspective of personal data resource allocation [15].

Therefore, by taking China's online car-hailing platform as the example, this research asks the following question: What is the market allocation structure of China's online car-hailing industry with perspective of the economics of personal data resources? To find the answer, this research adopts the network structural hole analysis method, which has been widely applied to studies of industrial competition within complex networks [16,17]. By combining multi-sided market and network structural hole theories, this research adopts the complex network analysis method to construct a personal data resource allocation network by analysing API relationship between selected platforms. From the perspective of the economics of personal data resource and analysis of the major network structural hole index, we have found a centralised structure of personal data resource among China's online car-hailing platforms. The accessing of personal data resource is becoming the elemental resource for platform rival. There is the potential risk of market power abuse that reduces the dynamic of sustainable innovation in the data-driven car-hailing industry.

2. Literature Review

The literature about the nature of economy and technology platforms includes five main topics. First, we briefly touch upon the open innovation paradigm. Second, we review the researches on the platform economy, addressing its online attributes. Third, related research of personal data resources is described, which has attempted to explain the characteristics of resource allocation of the online platform economy. Fourth, related research of the multi-sided market is detailed, which has revealed the market structures of the online platform economy for regulation purposes. Finally, research of network structural holes is described, which has explained the application domain of its research method. However, the allocation structure of personal data resource of the online platform is challenging the research paradigm of competition regulation and sustainable innovation governance.

2.1. Open Innovation Paradigm

Open Innovation (OI) is defined as "the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for the external use of innovation, respectively" [18]. OI is regarded as one of the important paradigms facilitating the micro dynamic entrepreneurial activities [19], bridging the connection between technology to market in business contexts [20], and constructing economic systems in macro-economic development [21]. Currently, OI has been widely adopted in managing platforms, embracing the external heterogeneous data and knowledge resources to complementing internal innovations within and across specific platforms [22]. Prior literature has largely emphasised the potential trade-offs between open innovation and appropriability in the context of platform economies, such as the two-sided market [23], open platform strategies [24] and platform governance [25], where an appropriate level of openness matters to the technological innovation and economic growth. We will review the relevant topics in the following sections.

2.2. Related Research of the Platform Economy

As an important part of the global economy, a platform economy relies heavily on the internet, for which data resources are at the core [26]. With the rapid development of information and communication technologies, both the concept and connotation of platforms have been expanded with characteristics distinct from traditional markets. First, the integration of massive data resources enables the platform to effectively and simultaneously coordinate supply and demand, reducing its severe information asymmetry [27–29]. Second, as the thresholds of information and communication technology use are further lowered, platform construction increasingly depends on the data generated by terminal customers or customer-derived content [30,31]. Third, online platform is considered as the

sustainable innovation platform by the aggregation of massive data resource for creating a large scale of data-intensive application scenarios [32].

The platform economy turns individual customers into non-eligible participants in the data-driven innovation process [33]. On the one hand, massive data resources act as raw materials for platform-knowledge production, and the data are provided by individual customers via their behaviours, preferences and attitudes towards privacy. On the other hand, more users participate in platform construction; they are responsible for more digitalised content and products, and they are important suppliers of knowledge production in the platform economy [34]. Finally, the platform construction process embodies the integration of information and communication technology with human social systems at a high level [35]. The constant innovation and iteration of information and communication technology development reflect the eager demand of society for information products and services. This rapidly and profoundly changes the modes of communication and production in human society [36]. Globally, the in-depth fusion of technological and social systems has become embodied in the rapid rise of the sharing economy [37,38].

2.3. Related Research on Personal Data Resources

Anonymised personal data are important structural resources in the platform economy [39]. First, the data carrying the most personal customer information constitute the premise for matching information within a multi-sided platform market. For example, the consumption preferences of users can offer accurate guidance for equipment manufacturers and third-party developers when implementing technical innovations and product improvements. Additionally, information on user behaviour serves as the basis for a precise advertisement launch [40]. Moreover, personal data resources are now critical guarantees for the high synergy of a multi-sided market [41]. Any type of data resource can be used and consumed by multiple stakeholders in different markets in real time [42].

From a multi-sided market context, consumption of data resources does not decrease market-resource allocation efficiency. Instead, it enhances the network externality of the platform. This means that more users can enhance the platform's control over the entire resource allocation network [43]. Finally, the size of the personal data resource is further extended as the platform economy develops. Owing to the 'locking effect' on users in a platform economy, when entering the multi-sided market, the user faces a fast-growing cost for switching to other platforms. This forces the users to account for the costs of technology, devices and habits. Therefore, a leading market platform is more likely to obtain more personal data resources [44].

2.4. Related Research on the Regulation of Multi-Sided Market

Platforms are equipped with conspicuous multi-sided market features [10]. The multi-sided market, also called the 'two-sided market', is a major market structure in the platform economy [45]. The platform economy involves multiple stakeholders belonging to other relatively independent consumer markets. Apart from platform-service suppliers, there are equipment manufacturers, communication service suppliers, third-party developers and individual customers to consider [46]. Each participating subject comes from a specific consumer market [47]. With the platform as the centre, multi-sided markets achieve a high synergy of market resources and information. The synergy of a multi-sided market makes it possible to optimise the profit sources of different markets [48]. Owing to the high efficiency of the profit compensation mechanism, the resource allocation model of the multi-sided market can make 'zero-price' products and individual-oriented services a reality [49]. However, the excessive competition of online platform by monopoly data resource will not only damages the social welfare, but also reduces the dynamic of sustainable innovation of digital economy [21].

The multi-dimensional structural pattern of the multi-sided market also causes governance difficulties [50,51]. The challenge mainly embodies the following three aspects. First, it is difficult to determine the market power of a platform based on a multi-sided market structure. A platform centred in a multi-sided market has strong controlling power of the information-resource network.

However, the power varies significantly with specific markets. For example, although the platform can analyse the supply chain of equipment manufacturers on the basis of their commercial intelligence system, it cannot directly control their supply chain [52,53]. Second, platform resource allocation in different markets is difficult to discern. Although manufacturers and developers choose platforms to optimise their market-resource allocation abilities, they significantly differ from each other when it comes to the demand for the platform [54]. Last, it is difficult to effectively measure the dynamic and static efficiency brought by platforms merged into the multi-sided market [51]. Platforms can acquire market resources, including personal data, from other platforms via mergers [55]. However, the merger of multi-sided market allocation differs from the horizontal and longitudinal centralisations of the traditional market. Thus, the improvement of efficiency resulting from platform mergers is not the same in all markets [56,57].

2.5. Related Research of the Network Structural Hole

As information and communication technology rapidly develops, the allocation of industrial resources tends to become networked [58,59]. The network structure of industrial resource allocations reflects the competing relationship and performance of enterprises in the market. This supports the formation of market competition networks [60,61]. In market competition, enterprises are never isolated subjects. Market behaviours and enterprise performance remain constrained, affected by other market participants and limited by network externality (i.e., Effective Network Size; ENS) [62,63]. Thus, on the basis of network constraints and ENS, the structural hole plays a vital role in the market competition network. Furthermore, non-negligible correlations exist between related indicators of structural holes and connectedness and connectivity among nodes in the network [16,64].

In the market competition network, the connectivity among nodes reflects the position of the enterprise in market competition connected with performance and innovation. The structural hole of the market competition network reveals the variation in market competitiveness among enterprises and the market-resource clustering structure to some extent [65]. Affected by the network's structural hole, enterprises located at the centre or at key market positions that exert large controlling effects on market-resource allocation [66,67]. Therefore, the theory of structural holes can provide a powerful explanation for the competitiveness and performance of enterprises in market competition networks [68].

Extant studies have focused on the analysis of the traditional market structure and the so-called supply-chain structure. The uncertainty and risk are hardly measured by the classical economic research methodology in the complex economic context [69,70]. Online platform economy is an essential part of the complex system of society and economy [71]. However, traditional research paradigms cannot satisfy the governance demand of the emerging data-driven platform economy. First, the governance of data-driven innovations requires a massive data allocation perspective within in a multi-sided market of dynamic development. Second, traditional antitrust devices cannot effectively measure the structure, channels and efficiencies of industrial mergers. Finally, there are few studies on the calculation and measurement of the edge weights of data resource connections, which is otherwise an essential index of structural hole detection within complex networks.

According to the discussion of related research, the allocation structure of industrial resource is the essential discussion of the study of competition regulation. However, the measurement of personal data resource allocation has become a major dilemma of research of regulation of platform economy. To address the challenges of the shifting big-data governance paradigm, this study establishes the personal data resource allocation structure as a precondition for empirical analysis. In accordance with the technical and economic feature of China's online car-hailing market, this study analyses the structural hole of personal data resource connectedness by addressing the mathematical modelling of the edge weights based on the analysis of sample platform APIs. Furthermore, this study discusses the status quo of the personal data resource market allocation structure and competition. By combining complex network analysis with multi-disciplinary research methods of computer science, this study

empirically analyses the status quo of the sample platform market driven by personal data resources to provide a theoretical basis for the research of sustainable innovation of digital economy.

3. Research Method and Hypothesis

Leading car-hailing platforms have spawned large-scale ventures with huge investments. Additionally, massive data resources have been generated by the diverse online customer presence on platforms. Car-hailing platforms also allocate massive data from terminal users. Personal datasets are critical resources of automatic driving, risk assessment and other artificial intelligence application scenarios [72].

According to prior research, the online platform economy presents a vivid network paradigm that allocates massive data via internet information and communication technologies, with the network approach of open innovation fitting well to support the analysis [73]. To answer the research question, we adopt multi-discipline methods, including system engineering, economics and computer science.

3.1. Definition of the PDRAN

To reveal the networked nature of personal data allocation, this research introduces the definition of the Personal Data Resource Allocation Network (PDRAN). PDRAN is the data network formed from anonymous personal customer data from different online car-hailing platforms via APIs. This concept comprises three elements: the online car-hailing platform, personal data connectedness and personal data connectivity. The definition of PDRAN reflects the networked nature of personal data resource allocation within platform economic contexts.

Online car-hailing platforms are closely related to social media. The development of APIs and related technologies has greatly promoted the transition of social media websites from Web 1.0 to Web 2.0, which is now one of the core technologies in platformisation. The real-time data exchange among social media platforms and terminal devices turns the social media platform into a highly dynamic data platform. Once entering the industrial domain, the dynamic social media data have the potential to create value accretion assets. Moreover, online car-hailing platforms have become an important domain in social media data applications.

Personal data connectedness indicates a connection and the connecting direction (i.e., data-transfer direction). There is a strong link between personal data connectedness and the construction of the online car-hailing platform. When data connectedness exists between the online car-hailing platform and end users, the platform collects preliminary individual travel data, comprising important resources of the online car-hailing platform construction. Because there is a network effect from the car-hailing industry, the volume of users' personal data collected by the platform positively relates to the network effect. Thus, the larger the network effect, the more users' personal data are collected. Motivated by acquiring more personal data resources, companies invest more into online car-hailing platform construction and innovation.

Personal data connectivity presents the scale and quality (e.g., data transmission rate, effectiveness and accuracy) of personal data connectedness and the service quality and user demand satisfaction achieved by the platform. The connectivity of personal data resources remains closely related to the functions of the online car-hailing platform, reflecting the demands of terminal users. This unveils the market relationship between online car-hailing platforms and other stakeholders.

The connectivity of personal data resources is positively related to the platform data resource aggregation ability. The higher the personal data connectivity of the online car-hailing platform, the stronger the ability of the platform in accumulating data resources and market control. Higher personal data connectivity among online car-hailing platforms signifies deeper partnerships. The connectivity is determined by the openness of the data terminal portal of the online car-hailing platform. The more open the data terminal, the stronger the connectivity of personal data resources.

3.2. Hypothesis

According to the network structural hole theory, structural holes in the market competition network are closely related to market-resource allocation and competition. Generally, structural holes are directly proportional to node connectivity, betweenness, *ENS* and the Burt constraint [68,74]. This suggests that higher indicators represent stronger effects of structural holes. When a structural hole effect in a market competition network is highly prominent, the resource allocation structure will be more centralised with more market resources aggregated by leading enterprises. This also reflects insufficient competition in industrial networks [75]. Given the multi-sided market theory and PDRAN features, according to discussion of the related research, we propose the following hypotheses:

Hypothesis H0. *If PDRAN's structural hole effect on online car-hailing platforms is insignificant, its market allocation structure will be distributed and personal data resource market competition will be adequate.*

Hypothesis H1. *If PDRAN's structural hole effect on online car-hailing platforms is significant, its market allocation structure will be centralised and personal data resource market competition will be inadequate.*

In H0, the structural hole effect of the sample platforms is insignificant that means the personal data resource can be well allocated by the sufficient market competition. There will not be any platform that can dominate or control the allocation of personal data resource on the industry level. Oppositely, the structural hole effect is significant in H1, which means that the personal data resource cannot be well allocated by the insufficient market competition. There will be the potential risk of market power abuse by the centralised structure of the personal data allocation with insufficient market competition. Furthermore, insufficient market competition will decrease the dynamic of sustainable innovation of the car-hailing industry. Consequently, by proposing the hypotheses, this research will try to answer the question of the personal data allocation mechanism, which is considered to be the critical issue of the domain of platform governance and data governance.

As shown as Figure 1, first, we raised the hypothesis from the dilemma of personal data resource allocation measurement of the prior literature. Second, we constructed network analysis model that including the mathematical model of the weight of edge of the sample network and the indicator system of the network structural hole. Third, we transferred the mathematical model into the code in R environment. By running of the code, the network visualisation and related indicators analysis will be presented. Fourth, we operated the robustness test to verify the analysis result. Fifth, we discussed the result to respond the research dilemma and drew a conclusion.
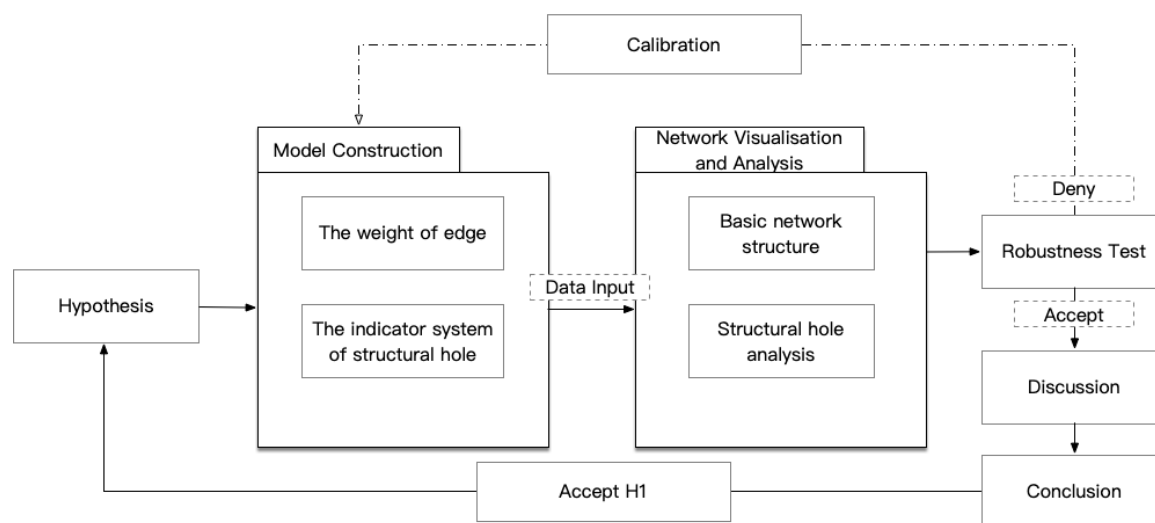

Figure 1. Hypothesis-testing process.

3.3. Assumption

Assumption 1. *To improve the reliability and validity of hypothesis testing, we identified the related preconditions as follows:*

Assumption 2. *Anonymous personal data resource can be transferred among the platforms via the market allocation mechanism;*

Assumption 3. *A personal data resource is an essential resource for multi-sided market competition;*

Assumption 4. *The scale of personal data resource is directly related to active terminal users on multi-sided platforms;*

Assumption 5. *Terminal users of the multi-sided platform market cannot directly control the data transferring among platforms;*

Assumption 6. *The cross-platform data connectivity reflects the controlling strength of the personal data resource being transferred among platforms and*

Assumption 7. *Cross-platform data connectivity is concerned with user scale and platform distance within the sample network. Furthermore, owing to network externality and the lock-in effect, cross-platform data connectivity is positively related to user scale. However, it is negatively related to the network distance of the platform.*

3.4. Device

This research used two steps of mathematical modelling to analyse the personal data resource allocation structure of the sample platform. In the sample network, each node stands for a single sample platform. Furthermore, each edge stands for the API relationship between sample platforms. According to the characteristic of the sample network, we constructed a gravity model of personal data resources to address the challenge of measuring the edge weights of the PDRAN. In addition, this research optimised the network structural hole measurement model by introducing the gravity model of personal data resources. The mathematical model is fundamental to the computational analysis of the network structural hole.

3.4.1. Model of the Weight of the Personal Data Resource Allocation

By analysing a network's structure, we determined the edge weight, one of the important preconditions. Edge weight is a feature of cross-platform personal data resource connectivity. Because market information remains asymmetric, when examining cross-platform personal data resource connections, they are difficult to accurately measure. Currently, the scale of active terminal devices is a significant indicator of platform competitiveness. A larger scale of active terminal devices usually indicates stronger network externality and lock-in effect. Consequently, it indicates higher market power and attraction for personal data resources. Therefore, on the basis of previous research of edge-weight calculation, this study employs the scale of active terminal devices to construct a gravity model based on the personal data resource connections among online car-hailing platforms to determine edge weights [76,77].

The PDRAN of online car-hailing platforms can be expressed as:

$$G_p = \left(V_p, E_p \right) \tag{1}$$

where G_p represents the PDRAN in the online car-hailing competition network, V_p is the set of nodes or platforms in the network and E_p is a set of edges in the network. When switched to be a square matrix. P_{ij}, and V_p can be expressed as:

$$V_p = \left(P_{ij} \right) \in \mathbb{R}^{m \times n} \tag{2}$$

where D_e is the direction of the edge in the network and $W_{o,i}$ is the weight of the edge in the network, including input and output. Thus, E_p can be expressed as:

$$E_p = (D_e, W_{o,i}) \tag{3}$$

In the PDRAN of online car-hailing platforms, $W_{o,i}$ is directly related to the data gravity among nodes and contains two variables: the strength of output P_{so} and the strength of input P_{si}, the connectedness of personal data resource. Thus, the data gravity strength constant among network nodes, d, represents the average node distance in the network. Thus, $W_{o,i}$ can be expressed as:

$$W_{o,i} = \mu \cdot \frac{(P_{so} \cdot P_{si})}{d^2} \tag{4}$$

To perform a comparative analysis of all nodes' personal data resource connectivity in the network, this study processes the edge weights using the non-dimensionalisation method. In this process, S_o is the scale of active terminal devices of a specific output connection node in the network, *max* S_o is the scale of the output node based on a maximum number of active terminal devices in the network, *min* S_o is the scale of the output node with a minimum number of active terminal devices, S_i is the scale of active terminal devices of special input connection nodes in the network, *max* S_i is the scale of the input node with a maximum number of active terminal devices and *min* S_i is the scale of the input node with a minimum number of active terminal devices. Therefore, P_{S_o} and P_{S_i} can be expressed as:

$$P_{S_o} = \frac{(S_o - min\ S_o)}{(max\ S_o - min\ S_o)} \tag{5}$$

$$P_{S_i} = \frac{(S_i - min\ S_i)}{(max\ S_i - min\ S_i)} \tag{6}$$

When Equations (5) and (6) are substituted into Equation (4), $W_{o,i}$ can be expressed as:

$$W_{o,i} = \mu \cdot \frac{\left(\frac{(S_o - min\ S_o)}{(max\ S_o - min\ S_o)} \cdot \frac{(S_i - min\ S_i)}{(max\ S_i - min\ S_i)} \right)}{d^2} \tag{7}$$

3.4.2. Model of Network Structural Hole

Indicators can be selected and combined in different ways to conduct an effective structural hole analysis on networks of varying types [75]. In view of the directedness and diversity of personal data connectedness of online car-hailing platforms, the indicators selected in this study to measure the structural hole of a network include betweenness $C_B(v)$, Effective Network Size (*ENS*) and Burt's constraint C_{ij} [75]. On the basis of these, a three-dimensional measurement model, S_h is established, expressed as:

$$S_h = F\{C_B(v),\ ENS,\ C_{ij}\} \tag{8}$$

This study first adopts the measuring method for complex network betweenness proposed by Brandes [78], which computes the betweenness of nodes in a sample network on the basis of minimum distance between nodes. In light of the directedness of the APIs, the result obtained in this study is the directed standard betweenness. v is a specific node in V_p, g_{ij} is the value of the geodesic from nodes i

to j and g_{ijk} is the numerical geodesic from nodes i to j passing through node k. Thus, the betweenness, $C_B(v)$, of the sample network will be:

$$C_B(v) = \sum_{i,j:i\neq j, i\neq v, j\neq v} \frac{g_{ijk}}{g_{ij}} \tag{9}$$

Second, the *ENS* and node constraint computing methods of Burt are adopted to determine the external constraint of platforms within the sample network and the *ENS* of personal data resource connectedness. The network's node constraint applies to redundancy. In the sample network, it is feasible to determine the effective network range according to the network redundancy of other nodes related to nodes j and i. This redundancy implies that the input or enabling related to node j is strongly connected to node q. Because p_{iq} represents the input or enabling related to node q in node i, and m_{iq} is the relevancy between nodes j and q affected by the strong connection between node j and others, the network redundancy, R, can be expressed as:

$$R = p_{iq} m_{jq} \tag{10}$$

On the basis of network redundancy, *ENS* can be determined:

$$ENS = \sum_j \left[1 - \sum_q p_{iq} m_{jq}\right], q \neq i, j, ENS \in [0, 1] \tag{11}$$

After network redundancy and *ENS* are determined, with p_{iq} representing the input or enabling related to node q in node i and p_{qj} representing the input or enabling related to node j in node q, the constraint, C_{ij}, between network nodes j and i can be determined:

$$C_{ij} = \left(p_{ij} + \sum_q p_{iq} p_{qj}\right)^2, i \neq q \neq j \tag{12}$$

On the basis of the equations above, this study selects iGraph, Social Network Analysis (SNA), influenceR, brainGraph and scatterplot3d in the R environment as primary research tools. iGraph and SNA are used to analyse and visualise the basic network structure. InfluenceR measures the structural hole-related indicators, and brainGraph performs robustness tests on the network structure. As shown in Figure 1, because the research subject is the online car-hailing platform, which depends strongly upon the massive data network built with information and communication technology, the network iteration value is as 10^5 to enhance the effectiveness of the robustness test, which determines the robustness of the network structure. The degree and betweenness of a new network generated by randomly increasing and decreasing the nodes and edges of the sample network (at a ratio of 15%). The result of the robustness test value is 1, indicating a random iterative increase or decrease will not materially affect the robustness of the network structure, because the structure is adequately robust and complete.

3.4.3. Data Sources

The samples selected for this study are influential platforms in China's domestic online car-hailing market. As shown in Table 1, 14 sample platforms were selected, accounting for 16.09% of online car-hailing platforms in 2018. Monthly terminal active devices (TADs) were over 20,000, and 94.45% of all the terminal devices were active (more than 20,000). Moreover, by considering the integration of the bike-sharing functions within the car-hailing platform market and the selection standard of the sample platform, this study includes three bike-sharing platforms: Mobike, ofo bike and Halo bike. ofo bikes can be directly accessed via terminal graphic interfaces.

Because Android OS is the most popular open-source intelligent terminal operating system in China, and the variation caused by mobile operation systems remains insignificant among online car-hailing platform users, this study selects the Android package (APK) for decompilation. Reverse software engineering is a highly efficient method of learning the structure of software from the source code. This activity also revealed the API document file, which is essential of depicting personal data connectedness. Furthermore, according to the laws of the U.S.A., the European Union, China and Japan, our reverse software engineering does not violate patent protection. There is a clear research purpose, study rationale and there are non-commerce applications [79–81].

All the data about sample platforms were collected from the internet. Those data can be roughly grouped into three categories: the APK used to generate source code for decompilation, source code data with a single iteration of decompilation for API relation analysis and statistical data about the size of active devices at app terminals. Single iteration of decompilation means that this research will not operate any other decompilation beyond sample APKs. According to the related legislation, the source code from decompilation will be used for the research purpose only. Detailed sources are as follows:

1. APK source: www.pc6.com (acquired on 16 August 2018)
2. API source: www.decompileandroid.com (acquired on 26 August 2018)
3. The fundamental statistical data of active device scale can be freely acquired from the official website of iResearch: www.iresearch.cn (acquired on 4 October 2018). iResearch is the leading platform of online users' statistic and market insights in China.

The following platform types will not be available for the calculation of connectivity using the number of TADs. However, further research should look at them. 1) Device manufacturer TADs' data analysis platforms will not be included, because their products, services and platforms are not directly related to terminal users. 2) We also do not include platforms in China with TADs below 20,000 per month, as of 31 October 2018. Consequently, there are 14 car-hailing platforms in the PDRAN with 41 platforms. (See Tables 2 and 3) Furthermore, owing to missing statistical data on specific platforms, we have removed 11 platforms with a not available (N/A) value in Table 2.

Table 1. Basic Information of the Sample Platform.

Content	Count
Sample Platform Count	14
Monthly Terminal Active Device (TAD) Amount of Sample Platform (by Oct 2018; 10,000 devices)	19,231
Total Car-hailing Platform Count	124
Car-hailing Platform (monthly TAD exceeds 20,000) count	87
Monthly TAD Amount of Car-hailing Platform (monthly TAD exceeds 20,000 devices by Oct 2018; 10,000 devices)	20,360
Percentage of monthly TAD of Sample Platform in Car-hailing Platform (monthly TAD exceeds 20,000)	94.45%
Sample Percentage of The Car-hailing Platform (monthly TAD exceeds 20,000 devices)	16.09%

4. Results

4.1. Multi-Sided Market Structure of the Sample Network

By analysing and visualising the basic structure of the sample network, we found that the PDRAN of online car-hailing platforms involved a variety of internet platforms, manifesting prominent features of a multi-sided market. As shown in Table 2 and Figure 2a, the sample network covers various internet platforms in fields, such as online car hailing, bike sharing, social media, online payment, map application, search engines, shopping and equipment manufacturing. In the sample network, online car hailing, social media, payment and map application platforms were the most abundant. Among the 41 platforms in the sample network, 14 (34%) were online car-hailing platforms, four (32%)

were platforms of social media (e.g., WeChat and QQ), payment tools and map apps. These platforms accounted for 66% of all platforms in the sample network and comprise the majority of the car-hailing multi-sided market.

Online car-hailing platforms can be further divided according to their specific types. Fourteen can be divided by two factors: passenger and driver. For example, DiDi Chuxing, DiDi Express (driver version), DiDi Chuxing (driver version) and DiDi Taxi are developed by DiDi for different terminal users in the multi-sided market. Similarly, Yidao, 01zhuanche and Meituan offer different platform services for passengers and drivers, and they integrate platform data resources through a data backstage with higher authority. It is noteworthy that personal data resource connectedness exists between online car-hailing platforms and bike-sharing platforms in the sample network. DiDi Chuxing and ofo bike blend the personal data resources of their terminal users to lay a foundation for a more efficient analysis of business intelligence by those platforms.

To observe the structural robustness of the sample network, this study randomly increased and decreased the nodes and edges (threshold: 15%) and tested the robustness of its betweenness and node degree. As illustrated in Table 3, with the iterated value set to 10^5, the robustness was 1 for both nodes and edges. This indicates the sample network can well maintain its basic structure when its nodes and edges are randomly increased and decreased.

4.2. Basic Conditions of Network Structural Holes

As revealed by our structural hole analysis, the sample network has significant hole features. In Figure 2c, after being processed using the Burt constraint algorithm, the sample network presented striking structural hole features. First, most platforms appeared to be highly centralised. Second, two platform clusters with no direct personal data resource connectedness were formed outside the centralised platform cluster. Nodes 5, 12, 16, 19, 39, 40 and 41 formed the upper-left platform cluster in Figure 2c, and nodes 7, 8, 11 and 29 form the lower-right cluster. Obviously, a structural hole exists between those two clusters. The sample platform and direct-connective platform assemble as two clusters with a stronger relationship of personal data allocation. Meanwhile, structural holes exist between each node within the two platform clusters, and different platforms in the same cluster are not directly connected in terms of personal data resource allocation. Table 2 excludes some platforms from the sample network when connectedness weight is considered. Judging from the diameters of the nodes formed by TADs on platforms, the scale of the two-platform-cluster TADs beyond the centralised one remains lower. Thus, the two clusters beyond the centralised one plays an insignificant role in the personal data resource allocation of the entire sample network.

4.3. Betweenness

An analysis of the indicators related to structural holes indicates that the network betweenness of online car-hailing platforms is relatively high, meaning that the platforms play a significant role of mediation and conduction in the multi-sided market allocation of personal data resources. However, in the sample network, WeChat was the most important mediating party. As shown in Table 2 and Figure 2d, WeChat presented the highest betweenness (270.38), which was 83.7% higher than Alipay (147.21). Moreover, Alipay's network betweenness was 80% higher than DiDi Chuxing, which was in third place. Online car-hailing platforms vary little in network betweenness. This reflects the significant mediating effect played by WeChat and Alipay in personal data resource allocation.

4.4. ENS

According to *ENS* analysis, at 29, 23 and 13, respectively, WeChat, Alipay and Amap took the top three places in the rankings (see Table 2). Among the online car-hailing platforms having the largest *ENS*, China Auto Rental ranked fourth. Regarding the Burt-constraint-based ranking, online car-hailing platforms ranked much higher, whereas their *ENS* remained lower. 01zhuanche (driver version) ranked first in terms of the Burt constraint, and its *ENS* as only 1. It had an altogether low

ranking with DiDi Express (driver version) regarding *ENS*. An *ENS* analysis on the sample network suggested WeChat, Alipay and Amap were the three most influential platforms in personal data resource allocation.

4.5. Burt Constraint

The Burt constraint represents the constraint degree of the specific node by other directly connective nodes in a network. The higher the Burt constraint value, the greater the dependency of specific nodes with other connective nodes. As revealed in the Burt constraint analysis, WeChat, Alipay and Amap were the last three platforms in the rankings with 0.02, 0.03 and 0.08, respectively (see Table 2). Apart from 01zhuanche, most of the online car-hailing platforms did not vary much. The value of the Burt constraints of most online car-hailing platforms seem to be diversified instead of being limited to a connection to a single platform (see Table 2). For example, the DiDi Chuxing platform is connected to different platforms, such as WeChat, Alipay, ofo bike, Tencent Map etc., for personal data resource allocation. 01zhuanche (driver version) appears to have a higher Burt constraint because of its reliance on the passenger-oriented 01zhuanche platform, WeChat and Amap. Moreover, the Burt constraint values of DiDi Express (driver version), DiDi Chuxing (driver version) and DiDi Taxi were behind that of 01zhuanche (driver version). DiDi platforms have strong constraints from other platforms in the sample network. By comparison, the Burt constraint value of the passenger-oriented DiDi Chuxing platform was only 0.13, which is low among online car-hailing platforms, implying that it was less constrained by others.
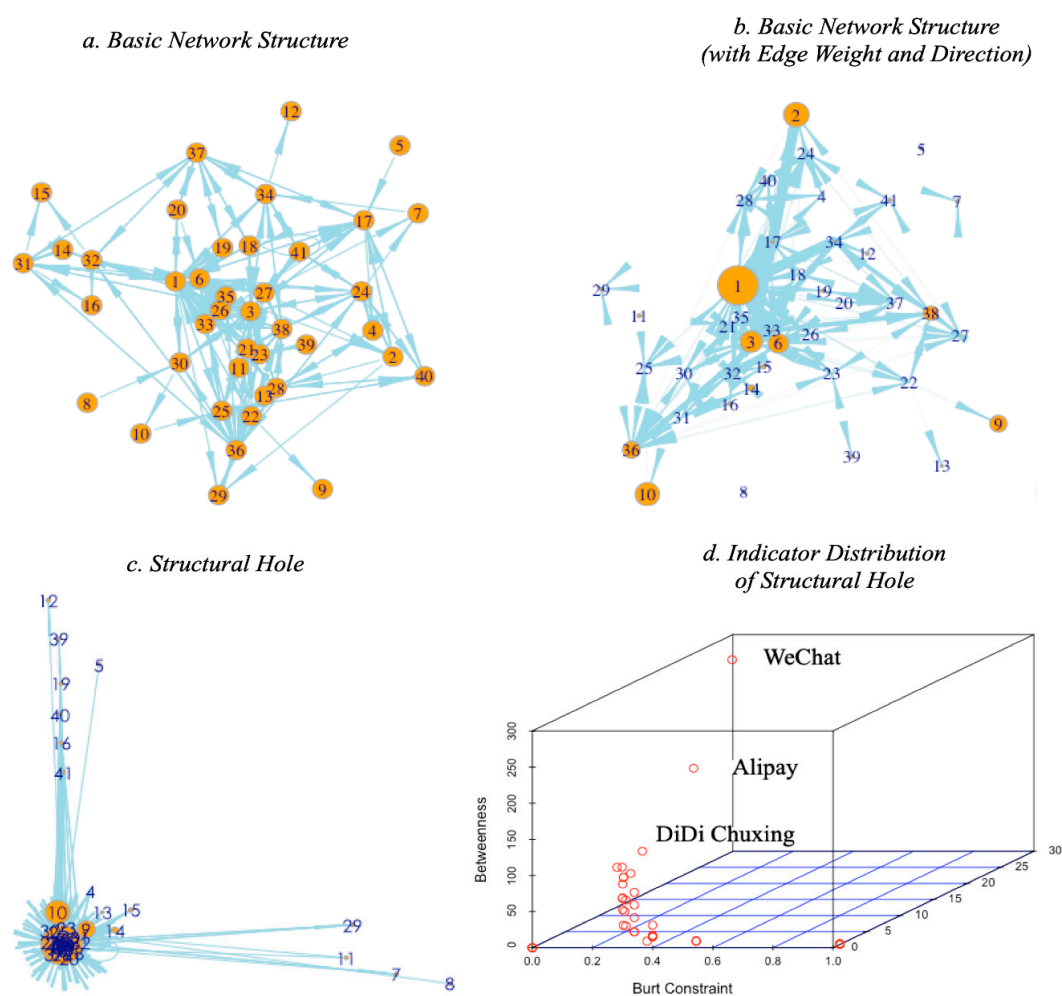

Figure 2. Network visualisation.

Table 2. Structural Hole Indicator Information.

Label ID	Platform Name	Platform Type	Betweenness	Burt Constraint	ENS	Label ID	Platform Name	Platform Type	Betweenness	Burt Constraint	ENS
1	WeChat	Social Media	270.48	0.02	29	24	China Auto Rental	Car-Hailing	53.81	0.08	11
2	QQ	Social Media	3.67	0.33	3	25	CAOCAO	Car-Hailing	41.47	0.25	4
3	Alipay	Online Payment	147.21	0.03	23	26	eHi Car Services	Car-Hailing	3.01	0.33	3
4	Jdpay	Online Payment	0.69	0.5	2	27	UCAR Inc.	Car-Hailing	28.22	0.1	9
6	Sina Microblog	Social Media	17.82	0.33	3	28	01zhuanche	Car-Hailing	25.73	0.17	6
10	Taobao	Online Shopping	0.21	1	1	29	01zhuanche (driver version)	Car-Hailing	1.45	1	1
14	Meituan	Life Service	0.14	0.5	2	30	GoFun	Car-Hailing	58.77	0.25	4
15	Dianping	Life Service	0.04	0	0	31	Us regiment taxi	Car-Hailing	61.8	0.13	8
17	DiDi Chuxing	Car-Hailing	81.75	0.13	7	32	Us regiment taxi (driver version)	Car-Hailing	61.8	0.13	8
18	DiDi express (driver version)	Car-Hailing	2.84	0.35	1	33	ofo bike	Sharing Bike	10.51	0.2	5
19	DiDi Chuxing (driver version)	Car-Hailing	1.81	0.33	3	34	Mobike	Sharing Bike	61.3	0.17	6
20	DiDi Taxi	Car-Hailing	1.81	0.33	3	35	Hellobike	Sharing Bike	7.67	0.2	5
21	Didapinche	Car-Hailing	23.72	0.25	4	36	Amap	Online Map	75.78	0.08	13
22	Yongche Inc.	Car-Hailing	80.31	0.14	7	37	QQ Map	Online Map	20.47	0.16	7
23	Yongche (driver version)	Car-Hailing	42.31	0.17	6	38	Baidu map	Online Map	25.8	0.11	9

Table 3. Basic information of the PDRAN structure.

Indicator	Value
Platform Count	41
Edge Count	193
Avg. Degree	4.707
Average Degree with Edge Weight	5.244
Density	0.118
Modularity	0.256
Average Clustering Coefficient	0.023
Average Distance	2.445
Robustness (Iteration: 10^3)	1 (Positive)
Robustness (Iteration: 10^5)	1 (Positive)

5. Discussion

According to the analysis result, there is a significant structural hole in the PDRAN. Leading platforms occupy the network position with stronger betweenness, weaker Burt constraints and larger *ENS*s. Consequently, H1 is accepted. The centralised allocation structure of personal data resource is emerging. By detecting network structural holes, this research found that the connection with social media and online payment platforms enhanced the market power of China's car-hailing platform. The access capability of personal data is necessary for market power abuse. This research also offers an alternative path to analysis the personal data resource allocation mechanism with dimensionless method in the complex economic system when the 'supply and demand' mechanism is still unclear. The result offers the analysis evidence of optimizing the structure of resources allocation to avoid the risks of monopoly that reduces the dynamics of sustainable innovation. Furthermore, the result is trying to offer the empirical evidence for further reproducible research in the domain of platform economy governance and regulation.

5.1. Personal Data Resource Is an Essential Structural Component of the Sustainable Innovation of Online Car-Hailing Platforms

An empirical analysis of the PDRAN structure among China's online car-hailing platforms reveals that, for a typical multi-sided market, online car-hailing platforms gather several market stakeholders, including software suppliers, payment systems, map applications and drivers, which facilitate the interactions among the heterogeneous players in the context of open innovation to achieve the economics of platforms [82]. With the car-hailing platform at the centre, those stakeholders transfer data to highly coordinate user demand with the car service supply. Moreover, the platform economy achieves sustainable innovation through profit distribution and compensation mechanisms by aggregating personal data resource. Structural holes reflect the market-clustering structure and enterprise competitiveness in the market to some extent. The online car-hailing platform at the centre of the structural holes can usually enjoy more advantages in data resource allocation. Thus, it can better stand out from market competition. The structural hole-based analysis of the sample network can adequately reveal the status quo and mechanism behind data-driven online car-hailing market competition with personal data resource allocation.

5.2. The PDRAN of Online Car-Hailing Platforms Appears to Be Centralised

From the PDRAN construction and analysis, it is found that the present market allocation of personal data resources among online car-hailing platforms follows a trend of centralisation. This finds response the previous literature by concerning the platform studies in the open innovation context from structure perspective [83]. As shown in Figure 2, conspicuous structural holes can be detected in the PDRAN of online car-hailing platforms, and the market allocation structure tends to be centralised. Because many data resources gather on a few platforms, such as WeChat, Alipay and DiDi Chuxing,

market competition becomes inadequate. According to analysis of the multi-sided market structure, the PDRAN of online car-hailing business covers diverse internet platforms, such as online car-hailing platforms, online payment platforms, social media platforms and online map platforms. Nonetheless, most data resources are centralised on one or two platforms within each type, such as WeChat in social media, Alipay in payment platforms and Amap in online mapping platforms. The centralisation trend of PDRAN raises the barrier for competitors entering the market. Insufficient market competition, therefore, may inhibit sustainable technological innovation.

5.3. Social Media Platforms Play an Essential Role in the PDRAN of Online Car-Hailing Platforms

The social media platforms represented by WeChat occupy the highest betweenness of all online car-hailing activities, far exceeding that of online car-hailing platforms themselves and equalling that of Alipay and DiDi Chuxing. This reflects the overwhelming effect of social media platforms in the PDRAN. Social media platforms can gather many users for the car-hailing platforms, and the massive user data provide the basis for profit making of the latter. For example, although Alipay of Alibaba Inc. is an online payment platform, it offers social networking services for terminal users. Online payment is also integrated into the elemental function of WeChat of Tencent Inc., one of the famous social media platforms in China.

Social media platforms mediate the delivery of data to the car-hailing platforms via bridges. The government should be cautious about exerting uniform supervision and regulation on social media platforms while keeping an eye on car-hailing platform enterprises during information security management, industrial regulation and behaviour standardisation.

5.4. Data Access Discrimination Is Causing Market Power Abuse within the Online Car-Hailing Platform Industry

According to comprehensive studies, the formation of structural holes reflects the centralisation tendency in the PDRAN, and the high betweenness of social media platforms suggests their dominating role. The access discrimination of personal data resources is an emerging barrier of competition among online car-hailing platforms. Once a centralised layout is formed, the market competitive structure will be negatively affected by the platform, which has more market power to access personal data resource. Consequently, potential rivals will find it difficult to enter the industry. All the above-reported shed lights on the open innovation extent of the platforms, by contributing the paradox between granting access and control [84]. In the era of big data, the authority of data access presents market power opportunities for competition and innovation. Data access discrimination can worsen the difficulty of industrial regulation, and insufficient competition can increase systematic risks for industry development, causing businesses to suffer disadvantageous data-driven innovation, which provides implications on the governance of big data collaborations in open platforms [85].

6. Conclusions and Outlook

Our analysis found that the online car-hailing platform market has become a multi-sided market in which the PDRAN shows a significant structural hole effect representing the centralised structure of market resource allocation. The centralisation of personal data resources enhances the market power of the leading platforms in the context of open innovation. Because the market allocation of personal data resource features information asymmetry, the scale of cross-platform data resource allocation and platform industrial clustering size needs further analysis. With emerging data-driven innovative paradigms, data technology and social systems are fused in depth.

This analysis provides solid empirical evidence for platform economy research and policy-making practice in the domain of governance and regulation. Although this research answers questions of competition status quo in China's car-hailing industry using the optimisation of the network structural hole model, limitations remain. This study focused only on a specific type of service platform and did not test it in more scenarios. The rapid development of China's platform economy is inseparable

from its own market, policies and environment, thus, it needs comparative analysis to gain more findings. Future research can validate and supplement this discovery on a wider range of platform giants such as Facebook, Google etc., or other types of platforms, such as social media platforms and payment platforms. The research of governance and the regulation of data-driven platforms require more empirical study to provide an accurate and continuous measurement of cross-platform data resource connectivity.

Data-driven innovation brings a new impetus to industrial innovation, but it also causes unfair competition, price discrimination and other potential risks of social welfare loss caused by the market power abuse of controlling personal data. Several negative issues arising from data-driven innovation challenge governance. To govern data-driven innovation, it is necessary to address massive technical reform for data resource gathering and industrial dynamic efficiency and to simultaneously cater to the demand of industrial static efficiency of adequate market competition.

Furthermore, when switching governance paradigms, it is necessary to coordinate the sustainability, openness and externality of innovation. Governance of online car-hailing platforms will involve more stakeholders, all playing a non-negligible role in data-driven innovation. Inadequate governance will allow a decrease of industrial innovation efficiency and negatively affect sustainable innovation.

There is a paradigm-switching period under way for platform competition research based on data resource's competitive strengths. The hybrid discussion about the technical and economic nature of data resources more accurately reflects the characteristics and development tendencies of platform trust. Currently, the negative issues arising from platform economic development should be solved with precise governance of the entire innovation ecosystem with emphasis on social responsibilities during the sustainable innovation.

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