Welfare and Distributional Consequences from Market Power in Markets for Digital Services and Interlinked Food Retail Markets: A Conceptual Note

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Abstract
Retailers of food and other consumption goods use households' private data to exercise market power through personalised advertisement and price discrimination. These data are obtained in interlinked markets for digital services, such as social media platforms and search engines. Consumers incur no financial costs when using digital services, but are required to reveal private information to use them. Those markets for digital services are characterised by market power, based on network effects and spiral effects, that can result in natural monopolies. Digital service providers can exploit this market power to extract more private information from their users than in a competitive setting. This increased amount of revealed private information then may result in financial disadvantages for households in the interlinked markets for food and other consumption goods.
Little conceptual or empirical work has been done so far to quantify the effects of this subtle yet drastic reshaping of many markets. No micro-economic model to date conceptualises the direct exchange of private information for digital services, and empirical work quantifying the welfare effects of market power exercised in digital service markets remains rare. This conceptional note lies the foundations for quantifying the welfare and distributional consequences of market power in food retail and interlinked markets for digital services.
While the literature provides some evidence on digital service providers' market power and on market power exercised in agricultural value chains based on data, no work has been carried out combining the two spheres. Therefore, the objective of this note is to develop a micro-economic model to allow for suitable representation of key characteristics of the market environment and capture the dynamics of food retailers' market power based on private household information.

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1. Introduction

The increasing direct exchange of personal data for digital services affects the nature of much economic activity. This development represents a transition beyond the conventional monetary exchange for the purchase of goods and services. Personal information serves increasingly as a form of payment when conducting certain transactions in markets for digital services (Malgieri and Custers, 2018).

Since markets for digital services are characterised by market power, the "price" at which the services are "paid" for in terms of how much private information a user has to reveal to obtain the respective service, is likely to be higher than it would be in a more competitive market environment (Kerber, 2016). The digital service providers sell their users' personal data for hard cash to traditional retailers, who use the data to price discriminate, segment markets, and for personalised advertising when marketing food and other goods to households (Spiekermann et al., 2015). One form of doing this is to sell online advertisement space targeted to only a group of individuals, based on their respective user profiles ("ad-discrimination", Malgieri and Custers, 2018) In agricultural value chains, the focus of research on market power based on information obtained online has been set on upstream stages of agricultural value chains: Just and Just (2006) find that online retailers of farm inputs engage in perfect discrimination of prices, based on the clickstream of the buyer. Regarding price discrimination towards consumers of agricultural and food products based on data obtained online, little research has been conducted so far.

Despite the new role of information as a form of payment, market power in interlinked food retail markets from the systematic combination and evaluation of large datasets is a growing blind spot in both conceptual and quantitative economics research. While aspects of privacy and approaches for regulation are discussed by a number of authors in the law literature, the economics literature focusses more on the implications within the markets for digital services, such as the households' valuation of privacy. Kerber (2016, p. 865) believes that "data protection provisions should be applied [...] only after an economic analysis of the expected effects". However, to the best of my knowledge, no work to date attempts to quantify the monetary welfare loss in interlinked food retail markets from the provision of digital services at a higher "price" than under competition. This conceptual note provides a contribution to closing that lacuna.

Market power in agricultural and food value chains has drawn considerable attention for decades, both in its oligopolistic and oligopsonistic form, as well as at all stages of the marketing chain. A summary of the literature is provided by Sheldon (2017), and earlier by Sexton (2000) and McCorriston (2002). Evidence for market power of food retailers is also ample. Sexton and Xia (2018) provide an extensive overview of findings on retailers' market power towards consumers from around the world. Substantial evidence suggests that one strategy of food retailers to exercise market power is through price discrimination. Cuellar and Brunamonti (2014) find that retailers of wine in the United States segment the market based on consumers' willingnesses to pay in each selected retail channel and price discriminate accordingly. According to Richards and Hamilton (2020), retailers engage in price discrimination based on quality differences in fresh food and vegetables in the United States. Gil et al. (2000) provide evidence for market segmentation by retailers based on regional preferences as well as consumer lifestyles and habits in markets for meat, fruit, and vegetables in Spain. Finally, Belz and Schmidt-Riediger (2010) provide evidence on how retailers can segment markets based on sustainability attributes of food products.

As the retailers' ability to exercise market power grows with an increasing data base, the interlinkage between food retail and markets in which payments are made via personal data constitutes a potential detriment to welfare. This is exasperated by the fact that network and spiral effects are characteristic for many markets for digital services, giving rise to natural monopolies (Vannini, 2004). Their resulting

market power enables the providers of digital services to obtain more private information from the users than they would in a competitive environment, leading to the amplification of market power in the interlinked food markets. Examples for information serving as payment are widespread, for example the use of social media or online search engines. Instead of incurring financial costs, social media and other digital services accept the personal information that users reveal automatically when using the platforms. Those include, for example, search terms in online searches, personel networks in messenger services, all private information that is uploaded to social media, etc. The suppliers of the services accept personal information as payment, because this data can be turned into money in the interlinked, traditional markets for food and other consumer goods.
To the best of my knowledge, no conceptional model exists that accounts for the monetary welfare effects in interlinked food markets caused by market power being exercised in the markets for digital services, despite informatisation being subject to scientific analysis across multiple dimensions (see next section). The goal of this conceptual note is to fill the lacuna in the agricultural economics literature on the analysis of market power in markets for digital services and related distributional and welfare consequences in interlinked food markets by theoretically conceptualising the distributional and aggregate welfare consequences from market power in markets for digital services in interlinked food markets. The target is to develop a micro-economic model to allow for suitable representation of key characteristics of the market environment and to capture the dynamics in food retailers' market power based on private household information. This work appears to be the first attempt to provide ideas on how to conceptualise such processes in economic theory. The concluding section provides ideas on the first steps required to empirically quantify those interrelationships.

2. Background

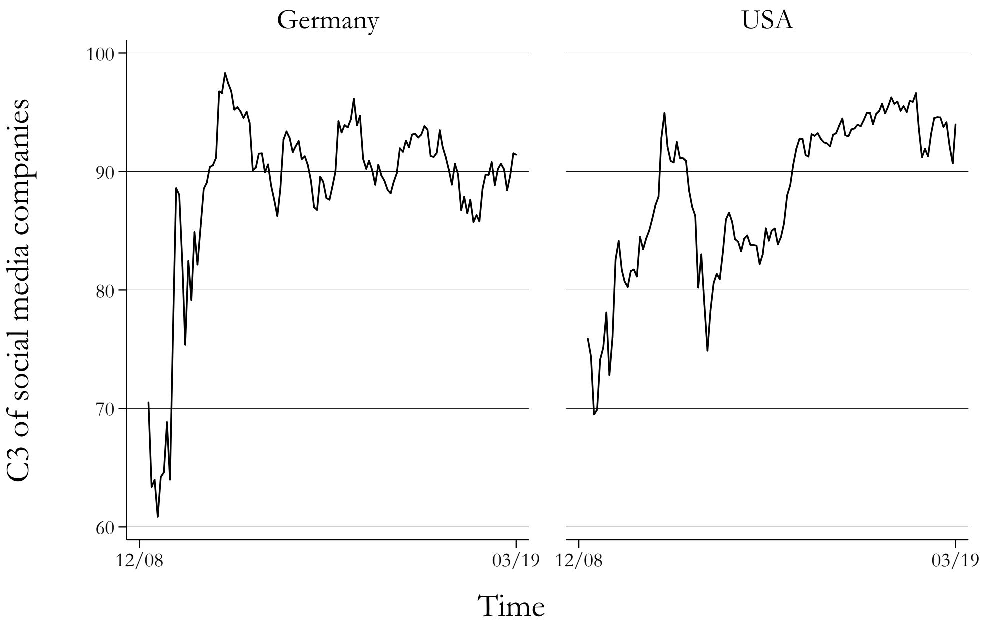
The transition from the mediation of market exchanges through monetary currency towards the direct exchange of private information for services may create monetary welfare losses in interlinked food markets. The fact that information partially replaces financial currency is not part of any existing theory, as micro-economic theories make evaluations generally in terms of monetary value. This section therefore provides the characteristics of markets for digital services, as well as information on demand for digital services that serve as foundations for the formal model to be developed in section 3. This section first lays out the reasons for and consequences from market power in markets for digital services, then elaborates on how these consequences cause market power in traditional markets before finally discussing resulting welfare implications.

2.1. Reasons for market power in markets for digital services

Markets for digital services, which are paid for through private household information, are often natural monopolies, or "winner-takes-all" markets (Vannini, 2004). Users subjectively benefit from many other users using the same service (network effects, Vannini, 2004; Varian, 2018) or an objectively increased quality of the service with a higher number of users (spiral effects, Lee, 2010). These characteristics can be found in markets for various kinds of digital services, such as social media or online search engines, which inherently require sharing private information (Trepte et al., 2019), and the online retail market, where transactions can only be completed once users have inserted private information (Alba et al., 1997; De Kervenoael et al., 2007). In social media, network effects increase individual users' utility as the user-base of the same service increases. Figure 1 provides anecdotal evidence for substantial consolidation over time in the social media market in two economies. In the market for online search engines, spiral effects increase the quality of the service, as the provider can custom-tailor

the displayed results to individual users, based upon information collected from past "transactions", i.e., searches (Lee, 2010). In agricultural value chains, potential network effects have been discussed for input markets by Murphy (2006), who argues that the company Cargill holds a substantial amount of market information, putting them in an advantaged position vis-à-vis competitors.
An additional reason for monopolisation are substantial fixed costs (Kerber, 2016). High fixed costs relative to variable costs are inherent to most markets for digital services, as the bulk of the costs is spent for software development while variable costs, that depend on the number of users, such as data storage and processing capacity per user, are relatively low.

Figure 1: Development of concentration ratio in social media (2008-2019).



In food retail markets, that are interlinked to markets for digital services, firms can monetise their knowledge on households' private information via several channels, including the exercise of market power. The remainder of this section first describes the data that are routinely shared by households before discussing their monetisation.

2.2. Firms' appropriation of private household information

The information that households pay to digital service providers consist of households' preferences, characteristics, and behaviour (Kerber, 2016). Malgieri and Custers (2018) argue that what is actually making the data valuable is their combination, creating *digital identities*, which are worth more than the sum of the values of a person's attributes. The households' preference for privacy conflicts with the revealed preferences of people having seemingly no problem with sharing their information, given how much information is routinely revealed in social media or when using other digital services. This "privacy paradox" (Zhan and Rajamani, 2008; Kerber, 2016) is discussed by a number of studies on willingness to share data and monetary valuation of privacy. These studies usually ask for the willingness to pay for privacy (Krasnova et al., 2009) or conduct behavioural experiments (Acquisti et al., 2013). The evidence obtained in such studies is mixed, and researchers mainly find results to be very context dependent. They are affected by the order in which questions are asked and by whether the participants are either offered money to disclose data or asked to pay for keeping data private

(Acquisti et al., 2013).

Several authors have offered explanations for the apparent paradox (Zhan and Rajamani, 2008). Most prominent is the claim that there is little awareness amongst users that firms are able to extract revenue from knowing their data (Malgieri and Custers, 2018). This is not only caused by users' ignorance, but actively encouraged by digital service providers who are intentionally intransparent regarding the data they collect (Kerber, 2016). In their analysis of the users' awareness of their digital footprint, Vervier et al. (2017) find that the younger generation especially is less aware of the amount of private information they reveal. However, the premise behind the apparent paradox is likely not precise because this assessment only considers the costs in terms of revealing private information, and not the utility that individuals derive from the services received in exchange. When pondering about the tradeoff between their conflicting interests, the users may conclude that the benefits of personalised services outweigh the costs of giving up privacy (Trepte et al., 2019). Revealing private information may well just be worth it.

2.3. Monetarisation of private household information

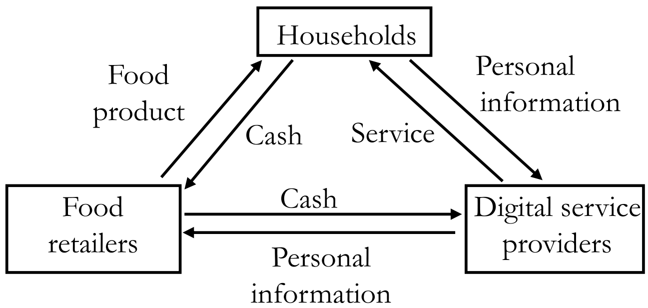
The data provided by households allows food retailers to exercise market power, both online and offline. Firstly, retailers can price discriminate by segmenting markets according to different willingnesses to pay and preferences of consumer sub-groups (Hui and Png, 2006; Belz and Schmidt-Riediger, 2010; Cuellar and Brunamonti, 2014; Richards and Hamilton, 2020), using detailed information on preferences and other characteristics like income to construct demand functions at the household level (Woerner and Wixom, 2015). Secondly, online retailers can engage in perfect price discrimination, i.e., offering specific prices to each individual buyer in accordance with their precise willingness to pay. Kerber (2016, p. 3) highlights that "price-setting algorithms cause prices to change constantly so that different persons can be offered different prices at the same time." Fudenberg and Villas-Boas (2012) formally show how information on household preferences can be used by firms to price discriminate, not only in non-competitive but also in competitive environments. Thirdly, online retailers *ad-discriminate*, meaning they show each individual user a selection of advertisements tailored to specific household characteristics (Kerber, 2016; Malgieri and Custers, 2018). Ad-discrimination can be exercised by both online and offline retailers in both online and offline micro-targeting of advertisements. Taylor (2004) finds that the price of advertisement space that can be customised based on the viewer's consumer profile is tenfold the one of untargeted advertisements.

The market interlinkage materialises in the existing, vivid market for household information obtained online (Taylor, 2004; Spiekermann et al., 2015). Hui and Png (2006, p. 477) refer to private information being acquired in one market and used in another one as "cross-market consequential externalities". A lot of research has been conducted on the existence of these markets, on the value of the data traded in these markets, and on possible regulation. Spiekermann et al. (2015) assert that – while discussion is still ongoing on how these markets should be regulated – they have already emerged. The regional differences in regulation between legal environments are substantial, allowing for "regulatory arbitrage" (Spiekermann et al., 2015, p. 162).

A discussion on how the value of personal data can be measured is provided by Malgieri and Custers (2018). Some issues that need to be considered is that the value of household data that a firm has access to depreciates over time (because of changes e.g., in income, preference, or address), that different users' data have different values (e.g., due to different household incomes or other, temporary specificities, such as sickness, grieve, or pregnancy), and that the data's initial "production" is - from the households' perspective - free of costs, i.e., the same amount of data can be shared multiple times or be copied by data traders at no costs (incrementally reducing the value of the data to users as it gives less of an advantage over competitors). The same authors evaluate the value of individuals' data, finding that most details shared on an individual are worth less than a dollar cent. Hacker and Petkova (2017) estimate that the value of one individual social media users' personal data is worth about one dollar per month.

The interlinked markets under consideration are displayed in figure 2, including the units of flows between market participants. As the figure illustrates, information is monetised by (food) retailers, who use households' private information as a mean to mark up prices. To do so, the information needs to be available as big data (for example gathered from many households) and combined with artificial intelligence, like machine learning and deep learning algorithms which recognise patterns in the data. Households, on the other hand, cannot derive a monetary value from their own data or exchange their data directly for money.

Figure 2: Flows of cash, information, goods, and services.



2.4. Welfare implications

To date little research has been published on the economic costs of digital monopolies to society. While some literature exists to provide solutions on how to increase privacy through market-based approaches (Krasnova et al., 2009), the most substantial share of research appears to be conducted on the legal aspects of the privacy issue (Kerber, 2016; Malgieri and Custers, 2018; Acquisti et al., 2013; Calo, 2011). In the economics literature, few authors analyse welfare consequences. The identified studies either conduct their analyses without a formal model (e.g., Hui and Png, 2006) or do not allow for quantification (Taylor, 2004; Fudenberg and Villas-Boas, 2012). No contribution has been found in the agricultural economics literature.

By paying with personal information, households incur two dimensions of disutility: a) a loss of privacy and b) monetary costs. Calo (2011) formalises these differences by defining subjective and objective harms to privacy. The former are associated with personal sentiments and distress while the latter include measurable, e.g., monetary, consequences. The subjective costs refer to the value households place on privacy, due to reservations against sharing private information with strangers (Rothfeder, 1992; Bergelson, 2005). Kerber (2016) argues that a pure economic welfare assessment does not include the normative dimension of privacy as a fundamental right and an end in itself.

The objective harms, i.e., the monetary costs, include the consequences of price discrimination and information asymmetry (Malgieri and Custers, 2018). Spiekermann et al. (2015) provide a broad discussion of the objective harms to privacy. The theoretical literature provides some findings on the effects of perfect price discrimination: Fudenberg and Villas-Boas (2012) find that in most cases consumer surplus and total welfare decrease when firms can use household preferences to price discriminate, unless possible competitors are aware of other firms having access to household information. With a modelling approach similar to Fudenberg and Villas-Boas (2012), Taylor (2004) finds that

selling user information reduces welfare, unless users anticipate this and behave strategically.
Interestingly, some authors observe beneficial effects in the economic dimension: While Zhan and Rajamani (2008) show concerns about the subjective dimension, they identify only the benefits from the economic perspective (increased efficiency, e.g., through lower search costs due to suggestion of new products), but do not consider monetary costs, for example due to market power. Spiekermann et al. (2015) add lower transaction costs within companies and mention increased returns from advertisement, also without acknowledging the market power component inherent to this practice.

3. Conceptual model

This section conceptualises the cornerstones of a micro-economic model which accounts for information as a form of payment and the value that households attribute to the privacy of information. To do so, the preference for privacy is added to the concept of household utility. The model is solved to derive equilibria in markets for digital services and interlinked food markets, accounting for both markets being characterised by market power.
The model includes private households, who demand digital services and a vector of consumption goods, including food products, as well as providers of digital services and retailers. In markets for digital services, households pay with their private information when purchasing such services. Network and spiral effects allow the producers of digital services to exercise market power over the households. In the interlinked market for food products, households pay with hard cash. The retailers can exercise market power based on the private information that have been previously obtained from households in the market for digital services. Because being subject to firms' market power increases the prices households have to pay for food and other consumption goods[1], giving away private information does not only cause disutility in itself, but also causes monetary costs in the interlinked market.

3.1. Model setup

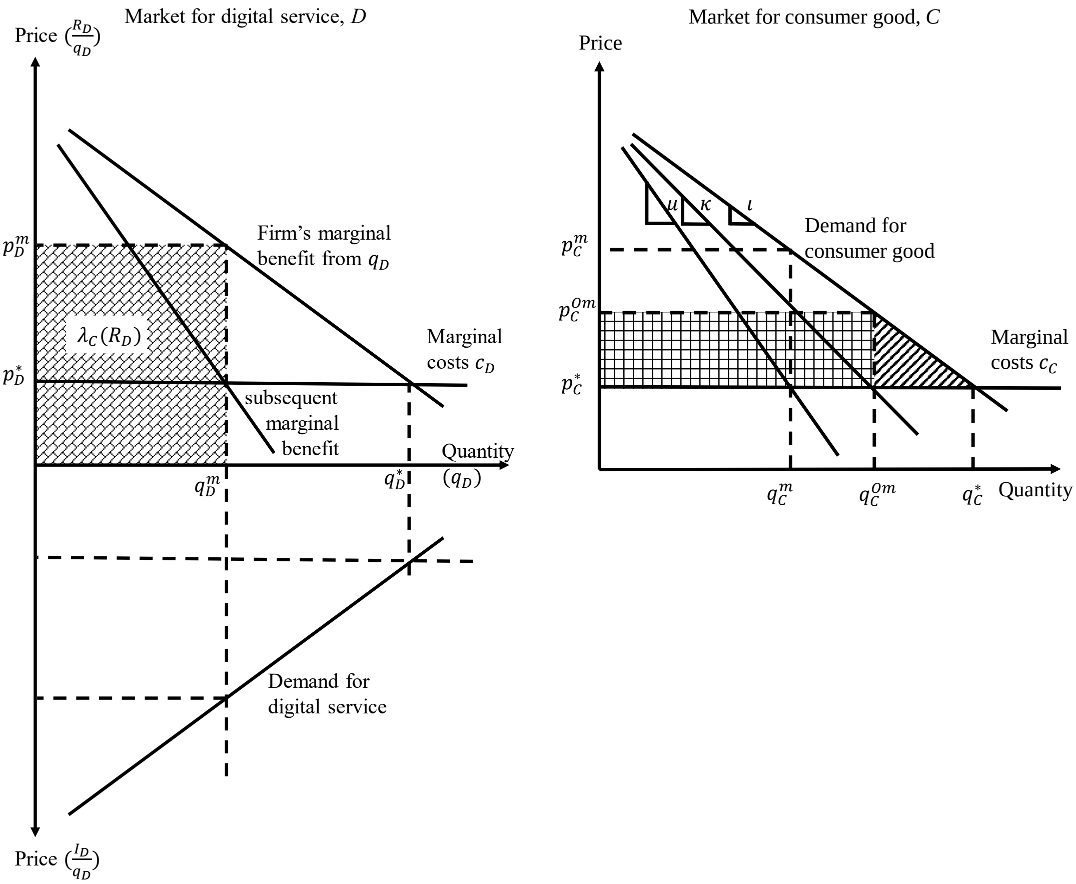
3.1.1. Market components

There are two markets: In market D, firms provide a digital service, which the households pay for by sharing private information, I. Network and spiral effects allow firms to mark up the amount of private information, p_D, that a household has to reveal to obtain one unit of the digital service. In market C, firms sell a food product, which households pay for with conventional, monetary currency. From the firms' perspective, market D only exists to obtain household information in order to exercise market power in market C.[2] The revenue that firms obtain in market D is the total amount of households' private information, R_D. Because knowing more about individual households' preferences enables firms to price discriminate, a positive value of R_D allows them to exercise market power in market C, i.e., marking up the price p_C above marginal costs[3]. All input markets are assumed to be competitive and firms have constant returns to scale technology, so the firms' supply function is a horizontal line. Figure 3 displays both markets and illustrates how market power in C is determined by the market power coefficient λ_C, which is, in turn, a function of the private household information, R_D, that companies obtain in market D. The vertical axis in market D is illustrated as two dimensions,

[1] It may be possible that price discrimination based on user data can actually lead to a decrease in consumer prices if the basic market structure is best represented by the Hotelling model and several assumptions are met (Stole, 2007; Thisse and Vives, 1988). I thank Matthias Hunold for highlighting this literature to me.
[2] To keep the model slim, the households' private information is the only source of market power available to the firms in market C. This assumption could be relaxed in future versions of the model developed here in which other reasons of market power can also be allowed for.
[3] See footnote 1 for a critical refletion on that assumption. Future versions of the model will explore alternative scenarios.

because prices paid by households are in another unit than that of the firms (amount of information revealed by households vs. monetary benefits from deriving those information and monetary costs of providing the digital service). The "revenue" obtained by the firm equals the financial advantage from the market power that the firm can exercise in market C based on R_D. The competitive price, p_D^*, is where this marginal benefit equals marginal costs, while the monopoly price, p_D^m, is defined by the intersection of the marginal cost and the *subsequent* marginal benefit, i.e., the *marginal marginal* benefit. Given that network and spiral effects tend to cause natural monopolies (Vannini, 2004), monopoly is assumed in market D.

Figure 3: Interlinked markets for digital service and food product.



Market power in market C is based on $\lambda_C(R_D)$, i.e., a function of the revenue obtained in market D, affecting market C as follows: κ is the λ_C-weighted mean of ι (perfect competition) and μ (monopoly), whereby $\mu = 2\iota$, so $\kappa = \kappa(\lambda_C) = \iota(1 + \lambda_C)$. Note that in the left diagram (market D), firms' marginal benefit is determined by demand for the digital service and the firms' increased profits in market C. The superscripts over prices and quantities denote the respective scenarios: In market C, q_C^m stands for monopoly in market C, q_C^{Om} for oligopoly power in C, based on monopolistic market power exercised in D, and q_C^* stands for competition in C. The quantity under moderate oligopoly power in C and competition in D (referred to as q_D^{O*} below) is located between q_D^{Om} and q_D^* not displayed in the graph. In market D, q_D^* stands for competition, q_D^m for monopoly.

3.1.2. Households

To conceptualise the payment of services with private information, the households' preference for privacy is introduced to the concept of household utility. The households' utility function is given by $U = f(q_C, q_D, I_D)$, in which q_C and q_D stand for the consumed quantities of the consumer good and digital service, respectively, and I_D is the total amount of private information revealed by the households with which they pay for the consumption of q_D. I_D enters the revenue function because sharing private data creates disutility for households. Households assign a high value to maintaining their privacy and not sharing their data for reasons of privacy. Their preference for privacy is conceptualised as the costs of sharing information with strangers which affect household utility in the form of a punishment term, which means that marginal utility of sharing private information is negative, i.e., $\frac{\partial U}{\partial I_D} < 0$. The marginal utility of consuming q_C and q_D, on the other hand, is positive. Revealing private information is of no direct monetary cost to households. However, as increased use of the digital service (D) gives firms the power to mark up the price of the consumer good (C), obtaining more of D causes a reduction in the consumption of C for the households, *ceteris paribus*.

Information can be multiplied indefinitely, which means that it can be repeatedly distributed to multiple service providers. Giving away the same information multiple times to different firms may be associated with increasingly less perceived disutility as one grows accustomed to sharing private information. However, giving away information, which is previously unrevealed, becomes increasingly expensive in terms of disutility. Further, consumers are heterogeneous in their privacy preferences (Kerber, 2016), as households vary in their valuation of privacy (Zhan and Rajamani, 2008). Krasnova et al. (2009) identify different segments of consumers with different privacy preferences. While personal data can be revealed by households in almost indefinite amounts, each household values it differently, depending on its individual preferences for privacy. This will cause the aggregate demand for digital services, paid for with private information, to be downward sloping, as illustrated by the following inverse demand function:

$$p_D = f(q_D) = g - hq_D, \quad | \quad g, h > 0 \tag{1}$$

in which q_D is the quantity of the digital service consumed and the "price" p_D is the amount of private information a household has to pay for one unit of the digital service.[4] Units are chosen such as to fulfil $g < 2.5h^{0.5}$. The total amount of information revealed by households (i.e., the revenue generated by firms in this market) is the amount of the digital service obtained multiplied by its price, p_D:

$$R_D = q_D p_D. \tag{2}$$

The inverse demand for the food product is given by

$$p_C = f(q_C) = a - bq_C, \quad | \quad a, b > 0 \tag{3}$$

in which q_C stands for the quantity of the consumption good purchased from the firms.

3.1.3. Firms

Households' private information is sold by providers of digital services to retailers of the food product, C. The retailers use this information to exercise market power in market C. Perfect competition is assumed between producers of digital services and food retailers. Therefore, private information is traded at a price equal to the marginal revenue it creates. This allows the simplification of the model in the sense that the two sectors' joint production decisions are modelled by conceptualizing them as one single firm.[5]. The cost functions assume competition in input markets and constant returns to scale technology, with c standing for the constant, per unit production costs of good C and d representing the per unit production costs of good D: $C_C = f(q_C) = cq_C$ and $C_D = f(q_D) = dq_D$. Total production costs are then given by $C_C + C_D = cq_C + dq_D$ and marginal costs are

$$MC_C = c \tag{4}$$

and

$$MC_D = d. \tag{5}$$

The firm is able to turn households' private information into monetary currency, as R_D allows it to raise the price in market C above the competitive level. This is conceptualised through the market power coefficient, $\lambda_C \in [0, 1]$, which stands for the degree of market power exercised in market C.

[4]The linear demand function is for illustrative purposes. In the future, a more flexible functional can be parametrised.
[5]This simplifying assumption can be relaxed in future iterations of the model developed here.

$\lambda_C = 0$ represents perfect competition and $\lambda_C = 1$ monopoly. Because the market power in market C is the result of the household information obtained in market D, the market power coefficient λ_C depends on the amount of information obtained in the market for digital services, i.e., the revenue generated in market D. Consequently, λ_C is a function of the quantity of private household information available to the firm, starting at 0 and ending at 1, given by

$$\lambda_C = \frac{R_D}{\overline{q_I}} \quad | \quad R_D \in [0, \overline{q_I}], \tag{6}$$

where $\overline{q_I}$ represents the maximum amount of private information that can be revealed by a household. Knowing all private household information gives the firm monopoly power in market C, while without any information on households, firms cannot exercise market power. In between the extremes, there is a linear relationship.[6] The total amount of private data that is provided by households as a payment for digital services, R_D, can be substituted by equation (2), yielding

$$\lambda_C = \frac{p_D q_D}{\overline{q_I}}. \tag{7}$$

3.2. Model solution

While the literature provides some evidence on the market power exercised in agricultural input markets based on data (Murphy, 2006; Just and Just, 2006) (but none at the food retailers' stage) and on the market power by providers of digital services (Kerber, 2016; Varian, 2018), no work to date has been carried out that combines the two spheres. This is crucially needed for an understanding of the welfare implications of these markets being interlinked: Firstly, when considering the markets for food products, the derived welfare losses are likely to be overestimated, because the benefits that consumers received (i.e. digital service) as compensation for their data are ignored. On the other hand, when looking at markets for digital services, the monetary losses to households due to revealing data are ignored.

3.2.1. Market solution for food product

Following Kopp and Sexton (2021), the quantity of the food product in the oligopoly setting, q_C^O, can be calculated as the weighted mean between the quantities under monopoly, q_C^m, and under perfect competition, q_C^*, with the weight being the market power coefficient, λ_C. To derive the competitive quantity, q_C^*, we set price, as given by equation (3), equal marginal costs of providing C, given by equation (4), and solve for q_C, yielding $q_C^* = \frac{a-c}{b}$. By inserting q_C^* into the inverse demand function (3), we get $p_C^* = c$ as the per-unit price. The monopoly solution is derived by letting the price depend on quantities, deriving marginal revenues, and then equalizing with marginal costs:

$$\frac{\partial \left(q_C \ p_C(q_C)\right)}{\partial q_C} = MC_C \quad \Rightarrow \quad q_C^m = \frac{a-c}{2b}. \tag{8}$$

The quantity is unambiguously positive because the existence of any production at all requires that the production costs of the first unit of output are less than the first consumer's willingness to pay, i.e., $c < a$. Inserting q_C^m from equation (8) into inverse demand (3) gives the price under monopoly, $p_C^m = \frac{a+c}{2}$. The quantity under oligopoly, q_C^O, is the mean of q_C^* and q_C^m, weighted by the market power coefficient, λ_C:

$$q_C^O = \left(1 - \frac{\lambda_C}{2}\right) \frac{a-c}{b} \tag{9}$$

The price of the food product under oligopoly is derived by inserting q_C^O into the demand equation (3):

$$p_C^O = c + \frac{\lambda_C}{2}(a-c). \tag{10}$$

[6]The linear relationship is assumed to avoid excessively complicated calculus in the following and can be replaced by a more flexible functional form.

The firm's total profit is given by the revenue generated in market C, i.e., the oligopoly price times oligopoly quantity, less all production costs:

$$\pi = \frac{\lambda_C(a-c)^2}{2b} - \frac{\lambda_C^2(a-c)^2}{4b} - dq_D \tag{11}$$

Equation (11) illustrates that there are only positive profits in the presence of a positive market power parameter λ_C.[7] This market power exercised in the market for the food product, λ_C, is given by equation (7) and substituted into the profit equation (11), yielding

$$\pi = \frac{p_D q_D(a-c)^2}{2b\overline{q_I}} - \frac{p_D^2 q_D^2 (a-c)^2}{4b\overline{q_I}^2} - dq_D = \frac{(a-c)^2}{2b\overline{q_I}}\left(p_D q_D - \frac{p_D^2 q_D^2}{2\overline{q_I}}\right) - dq_D. \tag{12}$$

In the subsequent calculus, Ξ replaces the constant term $\frac{(a-c)^2}{2b\overline{q_I}}$ for notational simplicity.

3.2.2. Market solution for digital services

In market D, households trade their private information for online services. To derive the benchmark equilibrium under competition in market D, we set profits from equation (12) equal to zero and solve for q_D:[8]

$$q_D = \frac{2\overline{q_I}}{p_D} - \frac{2d\overline{q_I}}{p_D^2 \Xi}. \tag{13}$$

We find the competitive equilibrium by inserting the inverse demand for q_D from equation (1) into (13) and solving for 0:

$$\begin{aligned} q_D &= \frac{2\overline{q_I}}{g-hq_D} - \frac{2d\overline{q_I}}{(g-hq_D)^2\Xi} \\ 0 &= q_D^3 - q_D^2\frac{2g}{h} + q_D\frac{g^2+2h\overline{q_I}}{h^2} + \frac{2d\overline{q_I}}{\Xi h^2} - \frac{2g\overline{q_I}}{h^2}. \end{aligned} \tag{14}$$

To identify the competitive quantity, q_D^*, equation (14) is solved for q_D. To do so we rely on the work of Cardano (1545) who provides the steps to solve three-degree polynomials which requires substituting the factors in the polynomial as follows: $k = \frac{2g}{h}$, $l = \frac{g^2+2h\overline{q_I}}{h^2}$, and $m = \frac{2d\overline{q_I}}{\Xi h^2} - \frac{2g\overline{q_I}}{h^2}$, so $0 = q_D^3 + kq_D^2 + lq_D + m$. We further define, following Cardano (1545), $\rho = l - \frac{k^2}{3}$, $\delta = \frac{2k^3}{27} - \frac{kl}{3} + m$, and the discriminant $\Delta = \left(\frac{\delta}{2}\right)^2 + \left(\frac{\rho}{3}\right)^3$. A cubic equation can have up to three real solutions and the number of real solutions is determined by the sign of the discriminant, Δ:

$$\Delta = \left(\frac{\delta}{2}\right)^2 + \left(\frac{\rho}{3}\right)^3 = \frac{\left(\frac{16g^3}{h^3 27} - \frac{2g(g^2+2h)}{3h^3} + \frac{2d}{\Xi h^2} - \frac{2g}{h^2}\right)^2}{4} + \frac{(6h-g^2)^3}{729h^6} \tag{15}$$

Given that units have been chosen to fulfil $g < 2.5h^{0.5}$, we can conclude that the discriminant $\Delta > 0$, which indicates that there is exactly one solution in the space of real numbers. The solution of the polynomial is given as $q_D^* = u + v - \frac{k}{3}$ (Cardano, 1545) with $u = \sqrt[3]{-\frac{\delta}{2} + \sqrt{\Delta}}$ and $v = \sqrt[3]{-\frac{\delta}{2} - \sqrt{\Delta}}$:[9]

$$\begin{aligned} q_D^* =& \frac{1}{3h}\sqrt[3]{-17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I} + \sqrt{\left(-17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I}\right)^2 + (-g^2+6h\overline{q_I})^3}} \\ &+ \frac{1}{3h}\sqrt[3]{-17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I} - \sqrt{\left(-17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I}\right)^2 + (-g^2+6h\overline{q_I})^3}} \\ &- \frac{2g}{3h}. \end{aligned} \tag{16}$$

[7]There will be market power only if the firm engages in providing digital services – and only then there are positive costs for supplying q_D. The firm does not make negative profits if $\lambda_C = 0$.

[8]Note that we divide by q_D during this and the subsequent derivation. This is mathematically legal because the "trivial" solution of $q_D = 0$ is not further considered. It does exist in the model because one possible reason for the firm to make no profits is that market D does not exist, so no market power is exercised in market C. This solution is not followed up further, because the digital service market does exist in reality and is also desired to exist in the hypothetical, competitive counterfactual.

[9]See Appendix A.1 for the calculus.

To simplify the subsequent calculus we substitute $A = -17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I}$ and $B = -g^2 + 6h\overline{q_I}$ which gives

$$q_D^* = \frac{1}{3h}\sqrt[3]{A + \sqrt{A^2 + B^3}} + \frac{1}{3h}\sqrt[3]{A - \sqrt{A^2 + B^3}} - \frac{2g}{3h}. \tag{17}$$

Next, p_D^* is identified by inserting q_D^* into inverse demand for D, equation (1).

$$\begin{aligned} p_D^* =& g - hq_D^* \\ =& \frac{5}{3}g - \frac{1}{3}\sqrt[3]{A + \sqrt{A^2 + B^3}} - \frac{1}{3}\sqrt[3]{A - \sqrt{A^2 + B^3}} \end{aligned} \tag{18}$$

In the case subject to this analysis, network and spiral effects tend to cause natural monopolies (Vannini, 2004). Exercising market power means that the firm can set p_D, the price in terms of how much of the user's private information is required to purchase one unit of the digital service, above the competitive level. To derive the equilibrium under monopoly, one would normally set price equal to marginal costs. The marginal costs of producing the digital service are given by equation (5). However, because the firm's output in this market is paid for with private household information, we rely on the benefit that the firm generates from obtaining household information, i.e., the effect that q_D has on the revenue (via λ_C) as described by equation (7) and the revenue-part of equation (12). Omitting the cost component in equation (12), inserting the inverse demand for q_D from equation (1), and differentiating with respect to q_D gives the marginal revenue in market C, MR_C, with respect to increases in q_D. To find the monopoly solution, q_D^m, MR_C is set equal to the marginal costs of providing one additional unit of D:

$$\begin{aligned} MR_C =& MC \\ \frac{\partial R_C}{\partial q_D} =& \frac{\partial C}{\partial q_D} \\ q_D^3 + q_D\frac{g+2h}{2h} + \frac{d}{\Xi} - g =& 0 \end{aligned} \tag{19}$$

Using the Cardano formula again, we set $k = 0$, $l = \frac{g+2h}{2h}$, and $m = \frac{d}{\Xi} - g$ and $\rho = l - \frac{k^2}{3}$ and $\delta = \frac{2k^3}{27} - \frac{kl}{3} + m$. As before, the number of solutions is determined by the sign of the discriminant[10]:

$$\Delta = \left(\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2}\right)^2 + \left(\frac{g+2h}{6h}\right)^3. \tag{20}$$

The first term (to the power of 2) is always positive and the second term (to the power of 3) is positive because the part in the brackets is positive. As before, $\Delta > 0$ indicates that there is exactly one solution in the space of real numbers. The solution is given again as $q_D^m = u + v - \frac{k}{3}$ with $u = \sqrt[3]{-\frac{\delta}{2} + \sqrt{\Delta}}$ and $v = \sqrt[3]{-\frac{\delta}{2} - \sqrt{\Delta}}$:[11]

$$q_D^m = \sqrt[3]{-\frac{\frac{d}{\Xi} - g}{2} + \sqrt{\left(\frac{\frac{d}{\Xi} - g}{2}\right)^2 + \left(\frac{g+2h}{6h}\right)^3}} + \sqrt[3]{-\frac{\frac{d}{\Xi} - g}{2} - \sqrt{\left(\frac{\frac{d}{\Xi} - g}{2}\right)^2 + \left(\frac{g+2h}{6h}\right)^3}} \tag{21}$$

.

Again, we substitute to simplify the subsequent calculus by defining $E = \frac{\frac{d}{\Xi} - g}{2}$ and $F = \frac{g+2h}{6h}$, so

$$q_D^m = \sqrt[3]{-E + \sqrt{E^2 + F^3}} + \sqrt[3]{-E - \sqrt{E^2 + F^3}}. \tag{22}$$

p_D^m is found by inserting q_D^m into equation (1):

$$p_D^m = g - h\left(\sqrt[3]{-E + \sqrt{E^2 + F^3}} + \sqrt[3]{-E - \sqrt{E^2 + F^3}}\right). \tag{23}$$

[10] The derivation can be found in Appendix A.2.
[11] The derivation can be found in Appendix A.3.

3.2.3. Distributional consequences and welfare effects

The distributional effect and welfare loss are generated by first inserting p_d^* and q_d^* and then p_d^m and q_d^m into the oligopoly quantity and price of good C, equations (9) and (10), respectively, with λ_C replaced by equation (7):

$$q_C^O = \left(1 - \frac{p_D q_D}{2\overline{q_I}}\right) \frac{a-c}{b} \tag{24}$$

and

$$p_C^O = c + \frac{p_D q_D}{2\overline{q_I}}(a-c). \tag{25}$$

The supplied quantities in market C for the case of competition in market D, q_C^{O*}, are generated by inserting p_D^* and q_D^* into equation (9)[12]:

$$\begin{aligned} q_C^{O*} &= \left(1 - \frac{p_D^* q_D^*}{2\overline{q_I}}\right) \frac{a-c}{b} \\ &= \left(1 - \frac{h\left(-\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} - \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}} + \frac{5g}{3h}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} + \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}} - \frac{2g}{3h}\right)}{2\overline{q_I}}\right) \\ &\quad * \frac{a-c}{b}, \end{aligned} \tag{26}$$

and for monopoly in market D, q_C^{Om}, by inserting p_D^m and q_D^m from equations (23) and (22) into equation (9) with λ_C replaced by equation (7) in both cases:

$$\begin{aligned} q_C^{Om} &= \left(1 - \frac{p_D^m q_D^m}{2\overline{q_I}}\right) \frac{a-c}{b} \\ &= \left(1 - \frac{\left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right)}{2\overline{q_I}}\right) \frac{a-c}{b}. \end{aligned} \tag{27}$$

Equivalently, the respective prices, p_C^{O*} and p_C^{Om}, are generated by inserting first p_D^* and q_D^* and then p_D^m and q_D^m into (10), again with λ_C replaced by equation (7).

$$\begin{aligned} p_C^{O*} &= c + \frac{p_D^* q_D^*}{2\overline{q_I}}(a-c) \\ &= c + \frac{\left(\frac{5}{3}g - \frac{1}{3}\sqrt[3]{A+\sqrt{A^2+B^3}} - \frac{1}{3}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} + \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}} - \frac{2g}{3h}\right)}{2\overline{q_I}}(a-c), \end{aligned} \tag{28}$$

and

$$\begin{aligned} p_C^{Om} &= c + \frac{p_D^m q_D^m}{2\overline{q_I}}(a-c) \\ &= c + \frac{\left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right)}{2\overline{q_I}}(a-c). \end{aligned} \tag{29}$$

The welfare loss, W, is the result of market D not being competitive but a monopoly and displayed as the striped triangle in Figure 3. It is calculated as $W = (1/2)(q_C^{O*} - q_C^{Om})(p_C^{Om} - p_C^{O*})$:[13]

$$\begin{aligned} W = &\Bigg(-\frac{2g}{3h} + h\left(-\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} - \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}} + \frac{5g}{3h}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} + \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}\right) \\ &- \left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\Bigg) \\ &* \Bigg(\left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right) \\ &- \left(\frac{5}{3}g - \frac{1}{3}\sqrt[3]{A+\sqrt{A^2+B^3}} - \frac{1}{3}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} + \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}} - \frac{2g}{3h}\right)\Bigg) \\ &* \frac{(a-c)^2}{8b\overline{q_I}^2} \end{aligned} \tag{30}$$

with $A = -17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I}$, $B = -g^2 + 6h\overline{q_I}$, $E = \frac{\frac{d}{\Xi} - g}{2}$, $F = \frac{g+2h}{6h}$, and $\Xi = \frac{(a-c)^2}{2b\overline{q_I}}$. g and h are the parameters of the demand for the digital services and a and b for the food product.

[12]The derivation can be found in Appendix A.4.
[13]The derivation can be found in Appendix A.5.

d and c are the per unit production costs of the digital service and the food product, respectively. $\overline{q_I}$ represents the maximum amount of private information that can be revealed by a household.
The redistributive effect, S, (cross-hatched rectangle in Figure 3) is calculated as $S = (p_C^{Om} - p_C^{O*})q_C^{Om}$:[14]

$$\begin{aligned} S =\Bigg(&\left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right) \\ &- \left(\frac{5}{3}g - \frac{1}{3}\sqrt[3]{A+\sqrt{A^2+B^3}} - \frac{1}{3}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} + \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}} - \frac{2g}{3h}\right)\Bigg) \\ &* \left(2\overline{q_I} - \left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\right) \\ &* \frac{(a-c)^2}{4b\overline{q_I}^2} \end{aligned} \tag{31}$$

4. Conclusion: Research outlook

This note can be used as a basis for future work, both empirical and conceptual. In the theoretical dimension, the next steps would be to give up several simplifying assumptions for a more accurate representation of the markets under consideration. Three dimensions come to mind: The first regards the simplifying conceptualisation of providers of digital services and retailers as one single firm. While the assumption holds for online retailers (e.g., amazon), which act as providers of the digital service as well as benefiting from the private information they receive from their clients, in most cases the household data is traded from providers of digital services to food retailers. The assumption of them being one company implicitly assumes that the market for households' private information functions well. In reality, however, that market is not characterised by competition in all subsectors, as the markets for advertising on websites or in social media are dominated by a few big companies. This shortcoming in the model can be addressed by explicitly modelling the market for information. The second scope for expanding the model is to describe the demand for digital services and food products by a more flexible functional form, for example from the family of second-order Taylor series expansions (Generalised Leontief; Generalised McFadden; translog specification). The third way of expanding the model is to allow for a non-linear relationship between retailers' data on private households, R_D, and market power, λ_C, and to give up the assumption that a maximum amount of private information that can be revealed by a household, $\overline{q_I}$, actually exists. To allow households to reveal an indefinite amount of private information with λ_C converging to 1 with increasing R_D, functions such as $\lambda_C = 1 - e^{-R_D}$ or $\lambda_C = 1 - (R_D + 1)^{-1}$ could be employed, both subject to $R_D \in [0, \infty[$.
In the empirical dimension, the logical next steps would be to develop a procedure to measure demand for digital services and apply it to markets for social media, online searches, online shopping, etc. In a subsequent step, an empirical procedure could be developed to estimate the component of retailers' market power that is based on private household information, and apply it to online and offline food retailers in different settings.
Once the demand equations have been parameterized, the maximum amount of private information that can be revealed by a household has been determined, and cost structures of production have been quantified, empirical questions as the following can be answered, based on the theoretical model developed here: How does aggregate household preference for privacy, represented by demand for the digital service, affect the observed price for the digital service? (I.e., $\frac{\partial p_D^m}{\partial h}$ =?) What is the effect of market power in market D on the amount of private information revealed by households? (I.e., $\frac{q_D^* p_D^* - q_D^m p_D^m}{q_D^* p_D^*}$ =?) And finally, what is the effect of market power in market D on welfare and

[14] The derivation can be found in Appendix A.6.

distributional consequences? (I.e., $W = ?$ and $S = ?$)

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A. Appendix

A.1. Appendix 1

$$
\begin{aligned}
q_D^* =& u + v - \frac{k}{3} \\
=& \sqrt[3]{-\frac{\delta}{2} + \sqrt{\Delta}} + \sqrt[3]{-\frac{\delta}{2} - \sqrt{\Delta}} - \frac{k}{3} \\
=& \sqrt[3]{-\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2} + \sqrt{\left(\frac{\delta}{2}\right)^2 + \left(\frac{\rho}{3}\right)^3}} + \sqrt[3]{-\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2} - \sqrt{\left(\frac{\delta}{2}\right)^2 + \left(\frac{\rho}{3}\right)^3}} - \frac{k}{3} \\
=& \sqrt[3]{-\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2} + \sqrt{\left(\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2}\right)^2 + \left(\frac{l - \frac{k^2}{3}}{3}\right)^3}} + \sqrt[3]{-\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2} - \sqrt{\left(\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2}\right)^2 + \left(\frac{l - \frac{k^2}{3}}{3}\right)^3}} - \frac{k}{3} \\
=& \sqrt[3]{-\frac{\frac{2\left(\frac{2g}{h}\right)^3}{27} - \frac{\frac{2g}{h}\frac{g^2+2h\overline{q_I}}{h^2}}{3} + \frac{2d\overline{q_I}}{\Xi h^2} - \frac{2g\overline{q_I}}{h^2}}{2} + \sqrt{\left(\frac{\frac{2\left(\frac{2g}{h}\right)^3}{27} - \frac{\frac{2g}{h}\frac{g^2+2h\overline{q_I}}{h^2}}{3} + \frac{2d\overline{q_I}}{\Xi h^2} - \frac{2g\overline{q_I}}{h^2}}{2}\right)^2 + \left(\frac{\frac{g^2+2h\overline{q_I}}{h^2} - \frac{\left(\frac{2g}{h}\right)^2}{3}}{3}\right)^3}} \\
&+ \sqrt[3]{-\frac{\frac{2\left(\frac{2g}{h}\right)^3}{27} - \frac{\frac{2g}{h}\frac{g^2+2h\overline{q_I}}{h^2}}{3} + \frac{2d\overline{q_I}}{\Xi h^2} - \frac{2g\overline{q_I}}{h^2}}{2} - \sqrt{\left(\frac{\frac{2\left(\frac{2g}{h}\right)^3}{27} - \frac{\frac{2g}{h}\frac{g^2+2h\overline{q_I}}{h^2}}{3} + \frac{2d\overline{q_I}}{\Xi h^2} - \frac{2g\overline{q_I}}{h^2}}{2}\right)^2 + \left(\frac{\frac{g^2+2h\overline{q_I}}{h^2} - \frac{\left(\frac{2g}{h}\right)^2}{3}}{3}\right)^3}} - \frac{\frac{2g}{h}}{3} \\
=& \sqrt[3]{-\frac{\left(\frac{2g}{h}\right)^3}{27} - \frac{g^3 + 2gh\overline{q_I}}{3h^3} + \frac{d\overline{q_I}}{\Xi h^2} - \frac{g\overline{q_I}}{h^2} + \sqrt{\left(\frac{\left(\frac{2g}{h}\right)^3}{27} - \frac{g^3 + 2gh\overline{q_I}}{3h^3} + \frac{d\overline{q_I}}{\Xi h^2} - \frac{g\overline{q_I}}{h^2}\right)^2 + \left(\frac{g^2 + 2h\overline{q_I}}{3h^2} - \frac{\left(\frac{2g}{h}\right)^2}{9}\right)^3}} \\
&+ \sqrt[3]{-\frac{\left(\frac{2g}{h}\right)^3}{27} - \frac{g^3 + 2gh\overline{q_I}}{3h^3} + \frac{d\overline{q_I}}{\Xi h^2} - \frac{g\overline{q_I}}{h^2} - \sqrt{\left(\frac{\left(\frac{2g}{h}\right)^3}{27} - \frac{g^3 + 2gh\overline{q_I}}{3h^3} + \frac{d\overline{q_I}}{\Xi h^2} - \frac{g\overline{q_I}}{h^2}\right)^2 + \left(\frac{g^2 + 2h\overline{q_I}}{3h^2} - \frac{\left(\frac{2g}{h}\right)^2}{9}\right)^3}} - \frac{2g}{3h} \\
=& \sqrt[3]{-\frac{8g^3}{27h^3} - \frac{g^3 + 2gh\overline{q_I}}{3h^3} + \frac{d\overline{q_I}}{\Xi h^2} - \frac{g\overline{q_I}}{h^2} + \sqrt{\left(\frac{8g^3}{27h^3} - \frac{g^3 + 2gh\overline{q_I}}{3h^3} + \frac{d\overline{q_I}}{\Xi h^2} - \frac{g\overline{q_I}}{h^2}\right)^2 + \left(\frac{g^2 + 2h\overline{q_I}}{3h^2} - \frac{4g^2}{9h^2}\right)^3}} \\
&+ \sqrt[3]{-\frac{8g^3}{27h^3} - \frac{g^3 + 2gh\overline{q_I}}{3h^3} + \frac{d\overline{q_I}}{\Xi h^2} - \frac{g\overline{q_I}}{h^2} - \sqrt{\left(\frac{8g^3}{27h^3} - \frac{g^3 + 2gh\overline{q_I}}{3h^3} + \frac{d\overline{q_I}}{\Xi h^2} - \frac{g\overline{q_I}}{h^2}\right)^2 + \left(\frac{g^2 + 2h\overline{q_I}}{3h^2} - \frac{4g^2}{9h^2}\right)^3}} - \frac{2g}{3h} \\
=& \sqrt[3]{-\frac{17g^3 + 18gh\overline{q_I}}{27h^3} + \frac{d\overline{q_I} - \Xi g\overline{q_I}}{\Xi h^2} + \sqrt{\left(-\frac{17g^3 + 18gh\overline{q_I}}{27h^3} + \frac{d\overline{q_I} - \Xi g\overline{q_I}}{\Xi h^2}\right)^2 + \left(\frac{-g^2 + 6h\overline{q_I}}{9h^2}\right)^3}} \\
&+ \sqrt[3]{-\frac{17g^3 + 18gh\overline{q_I}}{27h^3} + \frac{d\overline{q_I} - \Xi g\overline{q_I}}{\Xi h^2} - \sqrt{\left(-\frac{17g^3 + 18gh\overline{q_I}}{27h^3} + \frac{d\overline{q_I} - \Xi g\overline{q_I}}{\Xi h^2}\right)^2 + \left(\frac{-g^2 + 6h\overline{q_I}}{9h^2}\right)^3}} - \frac{2g}{3h} \\
=& \sqrt[3]{\frac{1}{27h^3}\left(-17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I}\right) + \sqrt{\left(\frac{1}{27h^3}\left(-17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I}\right)\right)^2 + \left(\frac{1}{9h^2}\left(-g^2 + 6h\right.\right.}} \\
&+ \sqrt[3]{\frac{1}{27h^3}\left(-17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I}\right) - \sqrt{\left(\frac{1}{27h^3}\left(-17g^3 - 18gh\overline{q_I} + \frac{27dh\overline{q_I}}{\Xi} - 27gh\overline{q_I}\right)\right)^2 + \left(\frac{1}{9h^2}\left(-g^2 + \right.\right.}} \\
&- \frac{2g}{3h}
\end{aligned}
\tag{32}
$$

A.2. Appendix 2

$$
\begin{aligned}
\Delta &= \left(\frac{\delta}{2}\right)^2 + \left(\frac{\rho}{3}\right)^3 \\
\Delta &= \left(\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2}\right)^2 + \left(\frac{l - \frac{k^2}{3}}{3}\right)^3 \\
\Delta &= \left(\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2}\right)^2 + \left(\frac{\frac{g+2h}{2h}}{3}\right)^3 \\
\Delta &= \left(\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2}\right)^2 + \left(\frac{g + 2h}{6h}\right)^3 .
\end{aligned} \tag{33}
$$

A.3. Appendix 3

$$
\begin{aligned}
q_D^m &= \sqrt[3]{-\frac{\delta}{2} + \sqrt{\Delta}} + \sqrt[3]{-\frac{\delta}{2} - \sqrt{\Delta}} - \frac{k}{3} \\
&= \sqrt[3]{-\frac{\delta}{2} + \sqrt{\left(\frac{\delta}{2}\right)^2 + \left(\frac{\rho}{3}\right)^3}} + \sqrt[3]{-\frac{\delta}{2} - \sqrt{\left(\frac{\delta}{2}\right)^2 + \left(\frac{\rho}{3}\right)^3}} - \frac{k}{3} \\
&= \sqrt[3]{-\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2} + \sqrt{\left(\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2}\right)^2 + \left(\frac{l - \frac{k^2}{3}}{3}\right)^3}} \\
&\quad + \sqrt[3]{-\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2} - \sqrt{\left(\frac{\frac{2k^3}{27} - \frac{kl}{3} + m}{2}\right)^2 + \left(\frac{l - \frac{k^2}{3}}{3}\right)^3}} - \frac{k}{3} \\
&= \sqrt[3]{-\frac{m}{2} + \sqrt{\left(\frac{m}{2}\right)^2 + \left(\frac{l}{3}\right)^3}} + \sqrt[3]{-\frac{m}{2} - \sqrt{\left(\frac{m}{2}\right)^2 + \left(\frac{l}{3}\right)^3}} \\
&= \sqrt[3]{-\frac{\frac{d}{\Xi} - g}{2} + \sqrt{\left(\frac{\frac{d}{\Xi} - g}{2}\right)^2 + \left(\frac{g + 2h}{6h}\right)^3}} + \sqrt[3]{-\frac{\frac{d}{\Xi} - g}{2} - \sqrt{\left(\frac{\frac{d}{\Xi} - g}{2}\right)^2 + \left(\frac{g + 2h}{6h}\right)^3}}
\end{aligned} \tag{34}
$$

A.4. Appendix 4

$$
\begin{aligned}
q_C^{O*} &= \left(1 - \frac{p_D^* q_D^*}{2\overline{q_I}}\right) \frac{a - c}{b} \\
&= \left(1 - \frac{\left(\frac{5}{3}g - \frac{1}{3}\sqrt[3]{A + \sqrt{A^2 + B^3}} - \frac{1}{3}\sqrt[3]{A - \sqrt{A^2 + B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A + \sqrt{A^2 + B^3}} + \frac{1}{3h}\sqrt[3]{A - \sqrt{A^2 + B^3}} - \frac{2g}{3h}\right)}{2\overline{q_I}}\right) \\
&\quad * \frac{a - c}{b} \\
&= \left(1 - \frac{h\left(-\frac{1}{3h}\sqrt[3]{A + \sqrt{A^2 + B^3}} - \frac{1}{3h}\sqrt[3]{A - \sqrt{A^2 + B^3}} + \frac{5g}{3h}\right)\left(\frac{1}{3h}\sqrt[3]{A + \sqrt{A^2 + B^3}} + \frac{1}{3h}\sqrt[3]{A - \sqrt{A^2 + B^3}} - \frac{2g}{3h}\right)}{2\overline{q_I}}\right) \\
&\quad * \frac{a - c}{b}
\end{aligned} \tag{35}
$$

A.5. Appendix 5

$$
\begin{aligned}
W = (1/2)\Bigg(&\Bigg(1-\frac{h\left(-\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}-\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}+\frac{5g}{3h}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}+\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}-\frac{2g}{3h}\right)}{2\overline{q_I}}\Bigg)\\
&*\frac{a-c}{b}\\
&-\left(1-\frac{\left(g-h\sqrt[3]{-E+\sqrt{E^2+F^3}}-h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}}+\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)}{2\overline{q_I}}\right)\frac{a-c}{b}\Bigg)\\
&*\Bigg(\left(c+\frac{\left(g-h\sqrt[3]{-E+\sqrt{E^2+F^3}}-h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}}+\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)}{2\overline{q_I}}(a-c)\right)\\
&-\left(c+\frac{\left(\frac{5}{3}g-\frac{1}{3}\sqrt[3]{A+\sqrt{A^2+B^3}}-\frac{1}{3}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}+\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}-\frac{2g}{3h}\right)}{2\overline{q_I}}(a-c)\right)\Bigg)\\
=\Bigg(&\Bigg(\frac{h\left(-\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}-\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}+\frac{5g}{3h}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}+\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}-\frac{2g}{3h}\right)}{4\overline{q_I}}\Bigg)\\
&*\frac{a-c}{b}\\
&-\left(\frac{\left(g-h\sqrt[3]{-E+\sqrt{E^2+F^3}}-h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}}+\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)}{4\overline{q_I}}\right)\frac{a-c}{b}\Bigg)\\
&*\Bigg(\left(\frac{\left(g-h\sqrt[3]{-E+\sqrt{E^2+F^3}}-h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}}+\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)}{2\overline{q_I}}(a-c)\right)\\
&-\left(\frac{\left(\frac{5}{3}g-\frac{1}{3}\sqrt[3]{A+\sqrt{A^2+B^3}}-\frac{1}{3}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}+\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}-\frac{2g}{3h}\right)}{2\overline{q_I}}(a-c)\right)\Bigg)\\
=\Bigg(&-\frac{2g}{3h}+h\left(-\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}-\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}+\frac{5g}{3h}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}+\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\\
&-\left(g-h\sqrt[3]{-E+\sqrt{E^2+F^3}}-h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}}+\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\Bigg)\\
&*\Bigg(\left(g-h\sqrt[3]{-E+\sqrt{E^2+F^3}}-h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}}+\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\\
&-\left(\frac{5}{3}g-\frac{1}{3}\sqrt[3]{A+\sqrt{A^2+B^3}}-\frac{1}{3}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}}+\frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}}-\frac{2g}{3h}\right)\Bigg)\\
&*\frac{(a-c)^2}{8b\overline{q_I}^2}
\end{aligned}
\tag{36}
$$

A.6. Appendix 6

$$
\begin{aligned}
S =&\Bigg(\Bigg(c + \frac{\left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right)}{2\overline{q_I}}(a-c)\Bigg) \\
&-\Bigg(c + \frac{\left(\frac{5}{3}g - \frac{1}{3}\sqrt[3]{A+\sqrt{A^2+B^3}} - \frac{1}{3}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} + \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}} - \frac{2g}{3h}\right)}{2\overline{q_I}}(a-c)\Bigg)\Bigg) \\
&* \left(1 - \frac{\left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right)}{2\overline{q_I}}\right)\frac{a-c}{b} \\
=&\Bigg(\left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right) \\
&-\left(\frac{5}{3}g - \frac{1}{3}\sqrt[3]{A+\sqrt{A^2+B^3}} - \frac{1}{3}\sqrt[3]{A-\sqrt{A^2+B^3}}\right)\left(\frac{1}{3h}\sqrt[3]{A+\sqrt{A^2+B^3}} + \frac{1}{3h}\sqrt[3]{A-\sqrt{A^2+B^3}} - \frac{2g}{3h}\right)\Bigg) \\
&* \left(2\overline{q_I} - \left(g - h\sqrt[3]{-E+\sqrt{E^2+F^3}} - h\sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\left(\sqrt[3]{-E+\sqrt{E^2+F^3}} + \sqrt[3]{-E-\sqrt{E^2+F^3}}\right)\right) \\
&* \frac{(a-c)^2}{4b\overline{q_I}^2}
\end{aligned} \tag{37}
$$