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Identification of critical actors and paths of contamination in the Dutch broiler meat chain: investigating the robustness of graph-based traceability system

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ABSTRACT

Today's poultry supply chains are complex, involving a diversity of actors and product quality labels. Risks of contamination with bacteria, such as *Salmonella* and *Campylobacter* are high and do occur regularly. A traceability system that identifies the critical actors and paths of contamination is essential for all actors in the food system to ensure a safe and healthy food supply. In this study, we enhanced a gravity model used in previous studies, which was limited to the two parameters of *distance between actors* and the *capacity of actors*, using a resource allocation optimisation method that allows all parameters of interest to be incorporated in the estimation of the supply chain network. We applied the new gravity model to incorporate product quality label information to identify critical actors and pathways of contamination in the Dutch broiler meat supply chain network using publicly available trade and actor data. The results show that slaughterhouses and cutting plants have the highest betweenness centrality, making them critical actors for contamination spread across the supply chain, while two hatcheries were identified as top actors based on degree centrality, indicating their potential influence within their respective supply chains. The predicted sources and pathways of contamination in the Dutch broiler meat supply chain network were largely comparable with the previous study. Though the inclusion of product quality labels in the modelling in this study has limited impact on the estimated supply chain network compared with the previous study, as the critical actors process broiler meat of diverse quality labels, the results demonstrated the value of the resource allocation optimisation modelling for incorporating all relevant parameters to model the supply chain network. The results suggest that the graph theory approach is methodologically robust in its predictive power as more data and more categories of actors are included.

1. Introduction

The worldwide demand for poultry meat has increased over the past several decades. According to the Food and Agricultural Organization (FAO), the worldwide consumption of poultry meat has steadily risen from 38.2 million tonnes (MT) in 1991 to 121.6 MT in 2021 [1]. The rise is partly due to the rapid increase in the consumption of poultry meat in developing countries [2]; [3,4]. In the Netherlands, the number of slaughtered chickens has increased from 83,000 in 1961 to 869,380 metric tons (MT) in 2021 [1].

As poultry meat consumption has increased, so has the risk of contamination with foodborne pathogens such as *Salmonella, Campylobacter*, *Listeria monocytogenes*, *Enterohemorrhagic Escherichia coli* (EHEC) and *Staphylococcus aureus* [5]. In 2018, the Netherlands Food and Consumer Product Safety Authority (NVWA) published a report concerning the risks outlined above in the Dutch poultry meat chains and advised the need to improve the traceability of poultry products starting from feed up to the consumers [6].

Ideally, the tracking and tracing of food products should be conducted using operational and transactional data of individual and batch product data [7]; [8,9]. However, this is rarely feasible because the required data is generally not shared or unavailable, hindering the realisation of traceability systems based on actual transactional data. The next best approach for implementing a traceability system is to estimate the paths of contamination using publicly available seasonal or annual data reports, such as trade volume data. In Hao et al. [10], the

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authors used publicly available trade data to estimate the Dutch broiler meat supply chain network and build a traceability system based on it. In this context, the trade-related data pertains to factors such as the actors' production capacity or annual revenue, as well as the physical distance between these actors. They used the distance between actors as a proxy for potential trade relations, the closer the actors are located to each other, the more likely the actors are to trade with each other. They represented the estimated trade relationships as a directed graph and estimated the significance of the actors by the degree and betweenness graph centrality [11] of the actors.

The study of Hoa et al. was limited in terms of the data sources used and the gravity model [12] used to estimate the presence or absence of trade relationship between the actors in the chain. This in turn limits the methodological robustness of the approach because if parameters other than capacity and distance have a major influence, the predictive power of the gravity modelling can be negatively affected. We hypothesise in this study that that the methodological robustness and reliability of the predictive power of the graph theory based traceability system can be enhanced if data on more actors in the network and additional parameters, such as product quality label attributes (e.g. organic and free-range labels)—data which are often publicly available—can be incorporated in the gravity modelling.

This study improves the previous work of Hao et al. [10] in two major ways. Firstly, a gravity modelling based on the resource allocation optimisation method suggested by Bretthauer et al. [13] and Ventura & Klein [14] was used. This allowed us to determine not only the mere presence or absence of trade between actors but also the possible trade volume through optimisation. This approach enables the seamless incorporation of quality label information into the gravity model and, in fact, allows for the inclusion of any additional parameter of interest in the gravity modelling. Secondly, we distinguished between different actor types that were previously lumped together. In this study, rearing and broiler breeding farms are treated as two distinct categories, and hatcheries are now integrated into the graph analysis. The export of hatching eggs and one-day-old broilers is linked to the hatcheries, in contrast to their previous association with broiler breeding farms. The cutting plants are used as such, while they were not distinguished from general processing facilities in the previous study. Additionally, categories representing restaurant butchers and wholesalers were considered separately in this research, whereas they were previously categorised under consumers.

2. Material & method

2.1. Data collection

Data was collected from five different sources: Dutch Food and Consumer Product Safety Authority (NVWA), the Dutch Chamber of Commerce (simply called KvK, *Kamer van Koophandel*, in Dutch), the Dutch Central Bureau for Statistics (CBS), the Dutch association representing the broiler meat industry (NEPLUVI), its umbrella organisation AVINED (representing the entire Dutch poultry sector), and quality label organisations. In many cases, the data files were made available as PDF files and were converted to CSV (comma-separated values) files for processing and analysis.

2.1.1. Data from the Dutch Food and Consumer Product Safety Authority (NVWA)

NVWA provides lists of approved poultry chain actors on their website [15]. The lists “Establishments in the veterinary field” and “Food establishments” has been used in this study. The data contains information about the individual approved broiler meat chain actors in the following supply chain categories; rearing farms, broiler breeding farms, hatching farms, slaughterhouses, cutting plants and meat preparation establishments (Table 1).

Besides the approved establishments operating in the Netherlands, the NVWA provides the overview of actors which are allowed to export broiler meat. The actors are categorised by the country to which they are licensed to export [16]. Table 2 summarises the number of actors with significant export volumes that are included in the analysis.

Table 1
Overview of number of supply chain actors per category (source: http://www3.vwa.nl/, retrieved in February and March 2020).

Type of actors	Number of actors
Rearing Farms	268
Hatcheries	41
Broiler breeding farms	275
Slaughterhouses	27
Cutting plants	398
Minced meat, meat preparation, mechanically separated meat facilities	546

The export registration data files contain the actor's name, EU-issued approval number (also shown on product labels). Facility addresses and municipality of each facility were also available. The locations are used in the gravity model to calculate the distances to potential trading partners.

2.1.2. Data from the Dutch Chamber of Commerce (KvK)

The KvK data provides information on the type of activity for each actor, which was not available in the NVWA data. Company details were retrieved using the KvK search facility [18]. The KvK company structure, based on the Dutch Standard Industrial Classification (in Dutch, Standaard Bedrijfsindeling, SBI) codes [17] was used to classify poultry farms into specific categories such as companies producing egg-laying hens (SBI 01.47.1), producers of broiler chickens (SBI 01.47.2), mixed poultry farms (SBI 01.47.3), *etc.*

2.1.3. Data from the association of Dutch poultry processing industries

NEPLUVI provides data on slaughterhouses through its annual reports since 2007. For this research, the 2018 annual report [19] was used in which 19 slaughterhouses, 16 broiler farms, 2 laying egg farms and 1 duck farm are described.

2.1.4. Data from the Dutch Central Bureau for Statistics (CBS)

CBS publishes yearly counts of searchable datasets on the agricultural sector [20]. The filters used to retrieve the data for this research are: Year (2018), Municipalities (all), and Subjects (broiler chickens, parents of broiler chickens, companies with broiler chickens, and companies with parent broiler chickens). The yearly CBS data on broilers per municipality was used as capacity parameter in gravity modelling. The central location of each municipality is used to compute distances for the gravity model. Based on the 2018 CBS data, 191 municipalities contain farms with broilers, parent broilers, or both. An overview of number of broilers and the related farms per municipality is presented in Table 3. Since parent broiler farm and broiler farm located within a single municipality are counted separately, the sum of both broilers and parent broiler municipalities exceeds the total number of municipalities.

The second dataset CBS provides is the number of inhabitants per municipality [21], which is used as the last set of actors in the supply chain, which are consumers. The number of municipalities and inhabitants in the Netherlands in 2020 were 380 and 17,181,000,

Table 2
Export registrations per category in Dutch poultry meat chain (source: http://www3.vwa.nl/, retrieved on February 5, 2020).

Type of actors	Number of actors
Slaughterhouses	31
Cutting plants	73
Processing plant poultry	33

Table 3
Number of (parent) broilers farms per municipality.

	Number of birds	Number of farms	Number of municipalities
Broilers	61,540,825	641	177
Parent Broilers	9,241,403	244	89
Total	70,782,228	885	191

respectively.

The third dataset CBS provides is a translation table between place names and municipalities [22], which is important because a municipality may contain one or more towns and villages and some places (often large villages) could be divided into one or more municipalities. Data retrieved on March 25, 2020 shows that there are 2423 places, 380 municipalities, and 12 provinces. NVWA and NEPLUVI data is based on place names and were translated into municipality level using the translations table.

2.1.5. Quality-label data

AVINED provides information regarding the IKB (Integrated Chain Management, in Dutch, *Integrale Ketenbeheersing*) certificates per supply chain category, ranging from grandparent farms until slaughterhouses [23]. An overview of the number of certified actors per category is presented in Table 4.

Datasets were also available from the website of BeterLeven (associated with the "Better Life" certification of the Dutch Society for the Protection of Animals), the SKAL Biocontrol foundation (*Stichting Skal Biocontrole* in Dutch), EKO (an independent certification body for organic products in the Netherlands), British Retail Consortium Global Standards (BRCGS), International Featured Standards (IFS) and Quality and Safety (QS, Qualität und Sicherheit). An overview of the number of certified actors per product quality label retrieved from these sources is presented in Table 5. The datasets available at the references provided in the table generally provide the name of the actor, its location (place name), reference number (number given by the certification body), and the scope—EU-organic, BLK, BRC, EKO, FSSC (Food Safety System Certification)-22000 and QS.

2.2. Quality label aware traceability modelling

The possible existence of trade relation between two consecutive set of actors in the supply chain was estimated using distance between actors and trade volumes in previous studies on gravity modelling [10]; [30,31]. In this study, we hypothesise that the presence of trade relations between two consecutive actors will also be influenced by product quality labels such as organic and free-range labels. Given that many actors process products with diverse quality labels, it is crucial to explore methods for incorporating quality label data into the model and examine how this dataset enhances the predictive capability of the model.

Quality-aware gravity model can be incorporated into the gravity model by using an optimisation technique. In this study, we used the resource optimisation model suggested by Bretthauer et al. [13] and Ventura & Klein [14] given by Formula (1). Quality attribute is introduced by using a relation matrix $l_{a_z}(i,j)$, representing the possibility of a trade relation between nodes *i* and *j* based on the matching quality labels

Table 4
Overview of IKB KIP certifications per category.

Type	Number of certifications
IKB Kip - Rearing (gr)parent	233
IKB Kip - Grandparent – Parent	470
IKB Kip – Hatchery	62
IKB Kip – Broilers	1391
IKB Kip - Slaughterhouse/cutting plant	26

Table 5
Overview of certified actors per certification scheme in the Dutch broiler meat chain (retrieved between 12 and April 16, 2020). BL stands for Beter Leven, the number of stars represents the stars of BL label.

Type	Number of actors	Reference
BL ★	84	[24]
BL ★★	19	[24]
BL ★★★	32	[24]
EU-organic	17	[25]
EKO	18	[26]
BRCGS	46	[27]
IFS	54	[28]
QS	53	[29]

$q_{0..z}$. According to this optimisation model, suppliers and receivers are restricted to trading products of the same quality label, precluding any downgrading or upgrading of the quality label of products.

$$\text{Minimize} \sum_{i\in S} \sum_{j\in R} \sum_{q\in Q} v_{ijq} \times d_{ij} \quad (1)$$

Where:

S is a set of suppliers.

R is a set of receivers (customers).

Q is a set of quality labels.

v_{ijq} represents the quantities a supplier *i* supplies to a receiver *j* in quality-label category *q*; a missing subscript *i*, *j* and/or *q* means a total quantity summed over all suppliers, receivers and/or all quality-labels, respectively.

d_{ij} represents the distance between supplier *i* to a receiver *j*.

$\forall_i \in S \sum_{q\in Q} \sum_{j\in R} v_{ijq} = v_i$: constraint per supplier.

$\forall_i \in S, \forall_q \in Q \sum_{j\in R} v_{ijl} = v_{iq}$: constraint per supplier and certification.

$\forall_j \in R \sum_{l\in Q} \sum_{i\in S} v_{ijl} = v_j$: constraint per receiver.

$\forall_j \in R, \forall_q \in Q \sum_{i\in S} v_{ijq} = v_{jq}$: constraint per receiver and certification.

$\forall_i \in S, \forall_j \in R, \forall_q \in Q\ v_{ijq} \geq 0, d_{ij} \geq 0$: non-negativity constraint.

The model was solved in ILOG CPLEX Optimisation Studio, providing the quantities supplied and received by each actor. The resulting data were analysed using the R programming language and the *igraph* package to compute centrality measures, particularly betweenness centrality. The network was visualised using the software tool QGIS.

2.3. Vulnerabilities in the Dutch broiler meat supply chain

To assess the vulnerabilities in the Dutch broiler meat supply chain, two centrality metrics were used, which are the *degree* centrality and betweenness centrality.

2.3.1. The in-degree and out-degree centrality

The in-degree and out-degree centrality metrics measure how well connected an actor is locally within the supply chain network [32]. Degree centrality is of interest in understanding the local influence of actors; those with many direct connections (with high degree centrality) are more important in their immediate neighbourhood than those with fewer connections (with low degree centrality). Companies with a high in-degree are called vulnerable, as they have an elevated chance of getting supplied with a contaminated product by their suppliers; likewise, companies who do have a high out-degree could spread contamination more easily because of the high number of customers they have [31]. In this study, the degree centralities for the Dutch broiler supply chain are computed on three levels (actor, municipality, and supply chain step).

2.3.2. Betweenness centrality

Betweenness centrality is a metric that measures how frequently an actor belongs to the shortest supply chain link between primary producers, like hatcheries, and end consumers, *i.e.*, consumers. This metric identifies the actors that play vital roles as bridges within the network, thereby measuring the overall influence. These actors have an elevated potential to spread contamination broadly downstream across the supply chain network. In this study betweenness centrality is also calculated at three levels: actors, municipalities, and supply chain step.

3. Results

3.1. Actors in the chain and quality labels

Based on the collected data, the Dutch broiler supply chain is presented in Fig. 1.

The number of actors using a particular product quality label in each actor category is summarised in Table 6. The quality certificates issued to the actors were retrieved from the databases of the respective quality certification institutions. The BLK database features two distinct portals—one for actors involved in slaughtering and meat processing, and another for broiler farms. Due to confidentiality arguments no information was provided by the label institute on the BLK certifications of broiler farmers and thus the figures in Table 6 are therefore set at zero for these categories. The EKO certificate label for broiler farms is likely higher than indicated in Table 6 as the farmers' names from EKO certificate database could not be matched with the data from CBS database due to the absence of farmer names in the latter.

3.2. Vulnerabilities in the Dutch broiler supply chain

3.2.1. In- and out-degree centrality per actor

The harmonised dataset is used to calculate the degree centralities of the actors in the Dutch broiler meat chain. Table 7 shows the in-, out- and combined degree centralities for the top 10 ranking individual actors in the supply chain network.

The in-degree centrality list shows that all the top 10 critical actors are slaughterhouses, making them the most vulnerable actors to receive contaminated products, according to degree centrality. The top four slaughterhouses exhibit significantly higher in-degree centrality compared to the rest, indicating a greater vulnerability to contamination spread and thus the need for enhanced control mechanisms to prevent contamination in these facilities. The results show that 8 out of the top 10 entities from the previous study still match the current top 10 list and major actors, and particularly the slaughterhouses SH564 and SH553 remained in the top 5, which is most likely because slaughterhouses process diverse quality label products. However, the centrality rankings differ significantly, highlighting the effect of the additional data that incorporated more supply chain actors than those considered in the

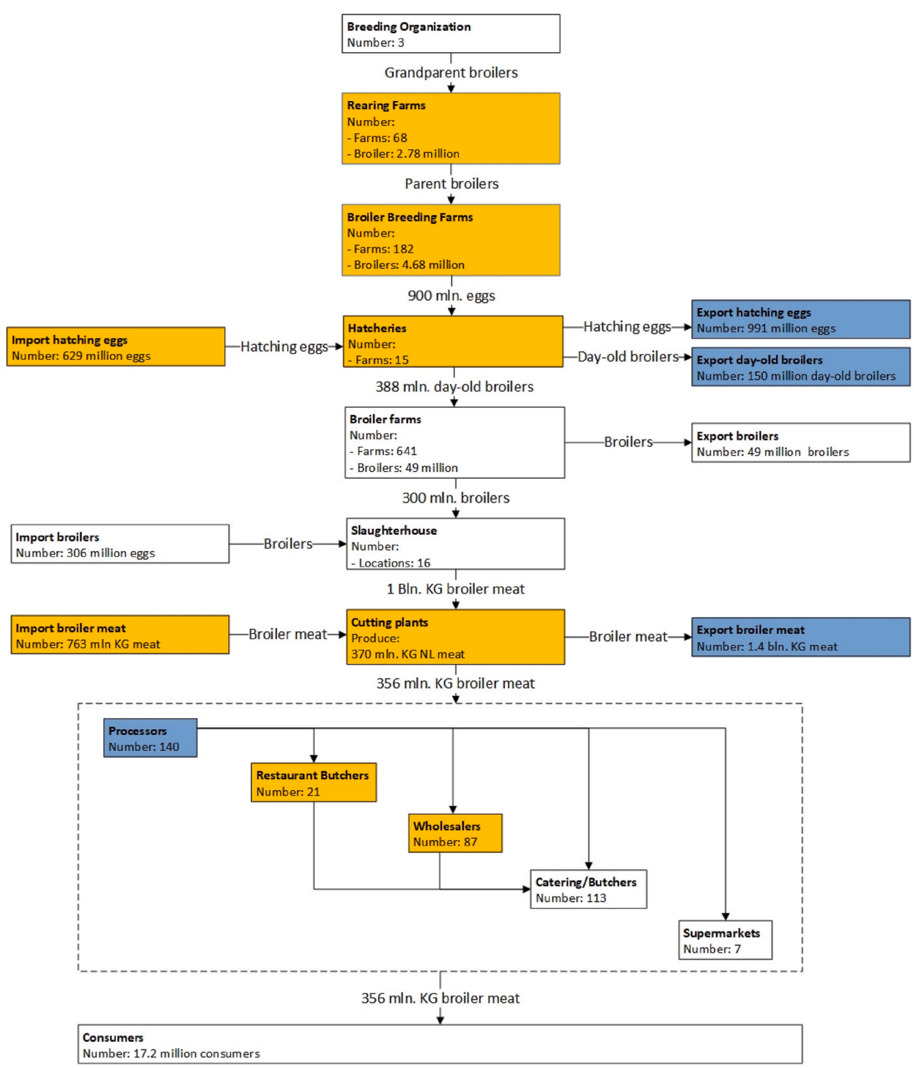

Fig. 1. *Representation of Dutch broiler meat supply chain*
Orange-highlighted boxes represent new additions and blue-highlighted boxes indicate elements with a new location compared to the previous research in Hao et al. [10]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 6
Number of actors per category per certificate in Dutch broiler meat chain.

	EU-Organic	BLK1	BLK2	BLK3	EKO	BRCGS	FSSC-22000	IFS	QS
RF	0	0	0	0	0	0	0	0	0
BBF	0	0	0	0	0	0	0	0	0
HAT	0	0	0	0	0	0	0	0	9
BF	9	0[a]	0[a]	0[a]	0	0	0	0	0
SH	1	5	2	2	1	13	1	2	4
CP	1	8	3	3	3	13	3	3	9
PR[b]	0	35	6	6	4	19	8	21	15
HB[b]	0	2	0	0	0	1	2	0	1
WS[b]	0	6	0	0	1	2	7	4	0
CB[b]	0	6	0	0	2	1	3	2	1
SP[b]	1	3	1	1	0	0	0	1	0
Total	**12**	**65**	**12**	**12**	**11**	**49**	**24**	**33**	**39**

RF = Rearing Farm, BBF = Broiler Breeder Farm, HAT = Hatchery, BF = Broiler Farm, SH = Slaughterhouse, CP = Cutting Plant, PR = Processing Plant, HB = Horeca Butcher, WS = Wholesaler, CB = Catering/Butcher, SP = Supermarket.

[a] Information regarding supply chain actors assigned to the category of broiler farm and BLK certificate was requested. However, the information could not be supplied due to confidentiality of information.

[b] *The list of establishments supplied by NVWA (2020c; 2020d; 2020e; 2020f) does not mention if an actor is active within the Dutch broiler meat chain. If an actor is active within the Dutch broiler meat chain, the lists do not state in which* category *they operate.*

Table 7
Actors with highest vulnerability.

Rank	In-degree centrality			Out-degree centrality			Combine centrality		
	Actor	Village	Degree	Actor	Village	Degree	Actor	Village	degree
1	SH561	Village166	123	HAT501	Village319	109	HAT508	Village420	133
2	SH560	Village93	105	HAT508	Village420	105	SH561	Village166	128
3	SH550	Village532	76	HAT522	Village496	87	HAT501	Village319	125
4	SH564	Village349	63	HAT520	Village270	72	SH560	Village93	108
5	SH553	Village 360	39	CP555	Village69	71	HAT522	Village496	100
6	SH551	Village 196	39	HAT526	Village453	70	HAT526	Village453	87
7	SH556	Village 272	38	HAT519	Village 337	44	HAT520	Village270	86
8	SH563	Village 264	36	HAT503	Village 141	44	SH550	Village532	77
9	SH557	Village 245	34	CP550	Village532	39	CP555	Village69	74
10	SH552	Village 557	30	CP621	Village 415	34	SH564	Village349	64

previous study.

The top out-degree actors are dominated by hatcheries and cutting plants, making them critical actors in their potential to spread contaminations. As the result, the top 10 ranking actors in the combined *in-* and *out-degree centrality* are hatcheries, slaughterhouses and cutting plants. Since hatcheries are a newly introduced actor type and more cutting plants are included in this research, the out-degree centrality rankings cannot be directly compared with those from the previous study; nevertheless, the results indicate how the inclusion of more data can yield new insights. The possible supply chain network based on in- and out-degree centrality is depicted in Fig. 2.

3.2.2. In- and out-degree centrality per municipality

Table 8 shows the top 10 ranking municipalities in terms of the in-, out- and combined degree centralities. The municipalities with highest *in-degree* centrality are Hardenberg, Hof van Twente and Ede, meaning these municipalities are more vulnerable to receive contaminated products. The underlying reason for Hardenberg's high score is a single actor, SH560, with a high *in-degree centrality*, which highlights the impact of a few large actors on the vulnerability of a specific geographical area. The municipality of Hof van Twente and Ede were also identified in the previous study [10] as top municipality in terms of in-degree centrality.

Someren, Meppel, and Dinkelland constitute the three highest municipalities in terms of out-degree centrality. The relatively proximity of the top four municipalities with high out-degree centrality indicates the potential risk of the spread of contagion from the region.

The combined in- and out-degree centrality shows that seven out of the top 10 municipalities on the list are in the middle and eastern part of the Netherlands, indicating that, in the event of a contamination outbreak, this particular area forms the highest risk for the spread of contamination, according to the degree centrality metrics.

3.2.3. In- and out-degree centrality per supply chain step

The vulnerability of each stage in the supply chain is investigated by computing the in- and out-degree centralities, as shown in Table 9. The table provides information on the number of actors within each supply chain stage, the estimated trade relations, and the minimum, median, and maximum in- and out-degree centralities. The results indicate that hatcheries are the most vulnerable to both receiving and spreading contamination. Slaughterhouses are most susceptible to receiving contamination, while cutting plants rank second to hatcheries in terms of vulnerability to spreading contamination.

3.2.4. Betweenness centrality per actor

Table 10 lists the top ten actors based on their betweenness centrality. The actors appearing in both the top ten combined in- and out-degree centrality and betweenness centrality are Hatchery 508, Slaughterhouse 561, Hatchery 501, Slaughterhouse 560, Slaughterhouse 550, and Cutting plant 555. Although hatcheries represent a new category in this study, making their associated results non-comparable to the previous study, CP619 was identified as one of the top-ranking entities in terms of betweenness centrality.

3.2.5. Betweenness centrality per municipality

Table 11 lists the top ten municipalities based on their betweenness centrality. A comparison between betweenness centrality and combined in- and out-degree results reveals that Doetinchem, Hof van Twente,

Fig. 2. The in- and out-centralities between (a) hatcheries and broiler farms, (b) broiler farms and slaughterhouses, (c) slaughterhouses to cutting plants, and (d) cutting plants to consumers (represented by municipalities).

Table 8
Municipalities with highest centralities.

Rank	In-degree centrality		Out-degree centrality		Combined centrality	
	Municipality	Degree	Municipality	Degree	Municipality	Degree
1	Hardenberg	131	Someren	128	Ede	193
2	Hof van Twente	129	Meppel	109	Hof van Twente	188
3	Ede	86	Dinkelland	108	Hardenberg	183
4	Doetinchem	83	Ede	107	Someren	167
5	Westerkwartier	75	Veldhoven	88	Dinkelland	140
6	Nijkerk	74	Mill en Sint Hubert	81	Doetinchem	126
7	Leudal	53	Stichtse Vecht	73	Meppel	126
8	Ooststellingwerf	51	Hof van Twente	59	Nijkerk	107
9	Nunspeet	42	Wierden	55	Mill en Sint Hubert	105
10	Someren	39	Nederweert	55	Veldhoven	103

Table 9
Overview table in- and out-degree per category.

Items		RF	BBF	HAT	BF	SH	CP	MUN
# Actors		68	182	15	641	16	29	380
# Trade relations		251	447	853	1295	701	453	397
In-degree	Min	–	1	2	1	1	1	1
	Median	–	1	14	1	35	1	1
	Max	–	4	28	2	123	6	4
Out-degree	Min	1	1	2	1	1	1	–
	Median	3	1	34	1	1.5	9	–
	Max	9	2	109	2	9	71	–

RF = Rearing Farm, BBF = Broiler Breeder Farm, HAT = Hatchery, BF = Broiler Farm, SH = Slaughterhouse, CP = Cutting Plant, MUN = Municipality.

Table 10
Actors with highest betweenness centrality.

Actor	Village	Betweenness centrality
CP619	Village 82	17782.83
SH561	Village 423	15444.71
CP550	Village 208	13446.85
SH560	Village 286	11988.61
CP555	Village 56	10050.92
HAT508	Village 98	9872.34
SH562	Village 268	9646.17
HAT525	Village 373	7672.01
HAT501	Village 249	7414.57
SH550	Village 246	6678.20

Table 11
Municipalities with highest betweenness centrality.

Municipality	Betweenness centrality
Doetinchem	20265.934
Son en Breugel	17941.975
Hof van Twente	15493.596
Stichtse Vecht	13666.458
Ede	13624.195
Hardenberg	12988.238
Westerkwartier	11322.803
Putten	10989.313
Dinkelland	10014.664
Nunspeet	9721.944

Ede, Hardenberg, and Dinkelland appear on both lists. All are located in the north-eastern part of the Netherlands, emphasizing the significance of the region in terms of the risk of contamination spread.

3.2.6. Betweenness centrality per supply chain step

Vulnerability in terms of the supply chain stage is also investigated using betweenness centrality as shown in Table 12. The results show that slaughterhouses and cutting plants have the highest betweenness centrality.

Further analysis reveals that only a couple of broiler breeder farms, particularly BBF264, have high betweenness centrality, while the rest have low betweenness centrality. In contrast, the betweenness centralities of hatcheries vary smoothly between the minimum of 116.69 (HAT507) and the maximum of 9872.34 (HAT508). It is worth noting that all hatcheries consistently exhibit a significant minimal betweenness centrality, implying that hatcheries can pose a persistent risk of contamination spread. Similarly, like broiler breeder farms, one broiler farm (BF1041) has a significantly higher betweenness centrality (1011.238), followed by a few others with quickly decreasing centralities, and the majority with very low betweenness centrality. The situation with slaughterhouses is like hatcheries, with differences in centralities being more spread. The situation with cutting plants is in between.

4. Discussion

In this study, we aimed to demonstrate an improved approach to gravity modelling based on a resource allocation optimisation method in constructing a supply chain network graph, thereby using the network graph to develop a traceability system to estimate critical actors and potential contamination pathways using a graph centrality approach. We aimed to demonstrate the methodological robustness by also incorporating more data and actor types into the model. A traceability system based on a graph network established from publicly available actor data not only addresses the typical lack of operational and transactional data on individual and batch-level products that are needed for tracking and tracing during contamination outbreaks, but also enhances the efficiency of planning preventive measures.

A previous study [10] used trade-related data pertaining to publicly available production capacities or annual revenues of actors, and the physical distance between the actors. In this study more actor types, additional data types (particularly product quality labels) and new gravity modelling to establish the supply chain network was used to both enhance the traceability model and demonstrate the methodological robustness in the face of the additional data used and changes in the gravity modelling approach.

The study of Hao et al. identified the need for more reliable and consistent trade data, information on known actual trade links, and the incorporation of additional factors influencing the possibility of trade, such as product quality hallmarks. In this study, we included additional data to enhance both the reliability and consistency of our findings. We also incorporated product quality labels into the model, necessitating a more flexible gravity modelling approach that allows the inclusion of parameters other than actors' capacity and the distance among them in the gravity modelling. Although the results of this study align with those of the previous study and provide greater insights, this study encountered also challenges due to inconsistencies and incompleteness of publicly available data.

Data inconsistency has been an issue at all stages of the supply chain. For example, data from NVWA and CBS presented inconsistent figures regarding rearing farms and broiler breeder farms. Even within the CBS data, related data were not always comparable due to different levels of data aggregation (i.e., national, provincial, farming region, and municipal levels). The NVWA supplied list reported inconsistent number of hatcheries, primarily due to the inclusion of hatcheries unrelated to the Dutch broiler meat chain. As a result, careful manual investigation using grey literature (e.g., news articles) and automated data analysis steps were required to verify data consistency and make the necessary alignments.

Missing data posed a significant challenge too. The CBS data only provided the number of broiler farms and broilers at the municipality level, with no detailed information at the village level. Detailed data on broiler farm characteristics, particularly regarding quality labels, was unavailable or some attributes of the actors, such as location, could not be aligned with the CBS data. As a result, broiler farms were treated as single entities without assigned quality labels. The capacity of each broiler farm was also estimated by dividing the total broiler population of a municipality by the number of broiler farms. Regarding slaughterhouse data, although capacity information is published by NEPLUVI, the reported capacity ranges sometimes differ significantly. Additional data were thus collected, resulting in updated capacities for all slaughterhouses except SH551, SH557, and SH565. The missing data were estimated using capacity-related data available from NEPLUVI.

In addition to inconsistencies and missing data, the need to gather and triangulate data from diverse sources posed an additional challenge. A notable example is the need to collect and verify quality certificates issued to various actors and estimate the percentage of products under each quality label. The quality certificates were verified through two methods: via the websites of the actors (mostly of slaughterhouses) and through the databases of the certification bodies. Combined with the absence of quality label data for broiler farms, the effect of quality labels on the gravity model remained limited. Regarding cutting plants, the data provided by NVWA included actors from later stages of the supply chain, such as processors, butchers, and supermarkets. Removing companies that are not classified as cutting plants according to EU Regulation 2007/834/EC required additional web-based data gathering and analysis. Both for this and other categories of actors, actors were also excluded when no data on capacity or revenue could be found.

Challenges also arose related to the downstream end of the supply chain, related to actors between stages of processing and consumers,

Table 12
Betweenness centrality per category.

Items	RF	BBF	HAT	BF	SH	CP	MUN
# Actors	70	182	15	641	16	29	380
Min	–	1.22	116.69	9.53	24.6	6.38	–
Median	–	72.43	2408.93	40.26	3311.27	530	–
Max	–	731.65	9872.34	1011.24	15444.71	17782.83	–

particularly concerning horizontal product flow. The list of establishments published by NVWA includes companies not only active as processors but also functioning as catering organisations, wholesalers, butchers, restaurant butchers, and supermarkets. A web-based analysis was conducted to classify individual actors and determine their capacity. During this analysis, it became evident that there is significant horizontal trade among actors within the same category. This could reduce accuracy, as the gravity modelling does not account for horizontal flows due to the general lack of data on trade relationships among actors of the same type.

The final data-related challenge pertains to the unmatched mass balance of supplied and received products. The number of broilers and the weight of broiler meat are based on data from CBS, NEPLUVI, NVWA, and other online sources. While the total volume of trade between two supply chain categories can be computed based on this data, the summed capacity of the supplying category of actors did not align with the summed capacity of the receiving category. Consequently, correction factors were calculated to reconcile supply and demand in the Dutch broiler meat chain. These correction factors are essential to ensure the usability of the optimisation model employed in gravity modelling.

The data gathered from the various sources exhibited significant inconsistencies and incompatibilities, which created challenges for harmonisation. This study demonstrated the implications for policy development in relation to data standardisation, metadata sharing, and harmonisation at various levels.

4.1. Limitations

Although this study addressed some of the limitations identified in previous research regarding the incorporation of more data, particularly data related to product quality labels, as well as the need for improved gravity modelling, other limitations from earlier studies persist, which have implications for future research and policy. First, the design of the supply chain network will be more reliable when it is based on data from the same year, preferably from the most recent year. This study faced challenges of inconsistent and missing data as outlined in the previous paragraphs. In addition, the available information on known actual trade links was not used in this study due to the challenges associated with verifying the information. However, incorporating known trade links into the modelling can be highly valuable for both improving network design and verifying the results of that design.

Second, the limitation stated in the previous study regarding the exclusion of indirect trades, such as product recalls, also remains relevant. The data analysis during this study also indicated a significant horizontal flow of products among actors within the same category, which is not accounted for in the modelling using in the previous and this study. These factors will affect both degree and betweenness centralities, thereby impacting the overall network design.

Lastly, the modelling is based on annual capacity or trade volume and does not account for the frequency and temporality of trade relationships. If an actor delivers or purchases products frequently, its degree centrality would be high; however, the modelling approach used cannot capture this, as it relies on aggregated annual data. Additionally, actors may experience seasonality in their trade activities, which is not considered in the modelling.

4.2. Further research and recommendations

The results of this research have several implications for future studies. Research on the digitalisation of the agri-food sector and the standardisation of data has gained significant attention and substantial funding in recent years (see, for instance, Ref. [33,34]). As operational data that could enable the tracking and tracing of food products remain inaccessible and as the publicly available date improve in extent, standardisation, and interoperability, future research could provide more accurate estimates of trade linkages and supply chain networks.

This research has also demonstrated how gravity modelling can be enhanced by employing more advanced optimisation methods. Future research could incorporate more comprehensive data, such as quality labels, seasonality, and the frequency of interactions. To achieve this, monthly or quarterly data could be used instead of annual data.

The results also highlight the value of publicly available data beyond its original intended use for transparency. This research demonstrates that such data can serve as valuable inputs for implementing traceability models, which are essential for safeguarding public health and ensuring the proper functioning of the meat sector. The findings underscore the need to incorporate data standardisation and interoperability mechanisms, which have proven their value and ease of implementation, into food policies.

5. Conclusion

In this study, an improved traceability approach for the Dutch broiler meat network based on graph theory is presented. The original traceability system based on a graph network design uses the trade capacity of actors and the distance between them. The approach assumes that actors are more likely to trade with other actors that are geographically close to them. Despite the simplicity of this assumption, the top three actors identified by the model of the previous study as being critical in the potential spread of contamination were confirmed by experts of the Dutch broiler meat industry.

However, when factors other than capacity and distance become significant, an approach based on this simple assumption could fail. We therefore enhanced the traceability model to allow additional significant parameters to be incorporated into the gravity model underlying the estimation of the supply chain network. We also used additional actor types, incorporated available quality label information, and improved the gravity modelling by using a resource allocation optimisation approach. By differentiating actor types, such as distinguishing between rearing farms and broiler breeding farms, and including hatcheries in the model, we were able to demonstrate the critical role of hatcheries. The improvement to the gravity modelling was also necessary to allow for more flexible constraint specification.

The inclusion of quality labels in this study did not have a major impact on the graph network because the data on quality labels were obtained only for slaughterhouses and cutting plants, and the proportions of products associated with different quality labels produced by these actors were not known. However, more data of public interest is increasingly becoming available, and this study provides a framework for future research with more detailed data. In addition, since transactional data, which is sensitive and internal to companies, will remain inaccessible, an improved traceability system based on publicly available data represents the next best approach, for which this study has presented a proof of concept to guide further investigations.

CRediT authorship contribution statement

Ayalew Kassahun: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Yamine Bouzembrak:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Tom de Reu:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Hans J.P. Marvin:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data sources are publicly available, with links provided in the manuscript. Intermediate data will be made available upon request.

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