EXPLORATORY ANALYSIS OF TRANSACTIONAL DATA TO AID IN THE SUPPLY CHAIN NETWORK DESIGN OF A FOOD BANKING NETWORK: A CASE STUDY

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ARTICLE INFO

Article details
Submitted by authors 27 Nov 2023
Accepted for publication 22 May 2024
Available online 30 Aug 2024

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DOI
http://dx.doi.org//10.7166/35-2-2986

ABSTRACT

This article applies a network lens to transactional data in order to improve a food banking network's supply chain design and planning. This study draws on data from FoodForward South Africa. This food bank has compiled a rich dataset of connections between supply chain partners (e.g., donors), the flow of stock (volume of food), and their beneficiary organisations. Our analysis showed an increase in the system's 'moving parts' (increased handling of donations), resulting in a significant imbalance between supply and demand. Additionally, in 2022, the organisation's warehouses received a larger number of smaller-volume donations from a wider variety of suppliers, placing an extra burden on the network.

OPSOMMING

Hierdie artikel pas ’n netwerklens op transaksionele data toe om ’n voedselbanknetwerk se voorsieningskettingontwerp en -beplanning te verbeter. Hierdie studie is gebaseer op data van FoodForward South Africa, ’n voedselbank wat ’n ryk datastel van verbindings tussen voorsieningskettingvennote (skenkers), die vloei van voorraad (voedsel volume) en hul begunstigde organisasies saamgestel het. Ons ontleding het ’n toename in die stelsel se ‘bewegende dele’ (verhoogde hantering van skenkings) getoon, wat gelei het tot ’n meer beduidende wanbalans tussen vraag en aanbod. Boonop het pakhuise in 2022 ’n groter aantal kleiner-volume skenkings van ’n groter verskeidenheid verskaffers ontvang, wat ’n ekstra las op die netwerk geplaas het.

1. INTRODUCTION

About 931 million tonnes of food produced globally for human consumption go to waste annually [1]. The amount of food wasted in South Africa alone is estimated at 10 million tonnes annually [2]. In addition, 7.0 per cent of households in South Africa have severe food insecurity, and 17.3 per cent have moderate food insecurity [3]. According to these statistics, the real issue is not food availability but how it is distributed to those in need [4]. Consequently, to combat these issues, food banks aim to reduce food waste and promote food security by redistributing abundant food supplies to beneficiary organisations [5].

Food banks face complex operational challenges owing to uncertainty in supply and demand [6]. They rely on donations from private companies and individuals, which are redistributed via non-profit organisations and government agencies [4]. Establishing lasting connections with supply sources and distribution partners is crucial for their operation [6]. However, capacity and time constraints, along with low supplies against demand, make it difficult to distribute the limited amount of donated food to the growing number of beneficiaries [7, 5]. As a result, food banks face difficulties in designing efficient supply chain networks, given the unpredictable nature of their operations. Capacity planning involves determining the size and capacity of facilities, while supply chain network design aims to optimise the configuration (i.e., number, type, and location of facilities) of a supply chain network, as shown in Figure 1.

This paper is part of a more significant project in which the optimisation of supply chains in the context of non-profit organisations, such as a food banking network, is studied. The project aims to determine whether the supply chain network design of an extensive network of food banks and their stakeholders is optimal and, if not, how it could be optimised to increase its impact and scale. Nevertheless, before determining whether the network is optimal for future operations, we must understand the current network, its characteristics, and the actual flow among entities. Therefore, this paper aims to understand better the current network design of a food banking supply chain network and how it has evolved over time to reach this point. FoodForward South Africa, a Global Food Banking Network member, is our case study pursuing this goal. This paper intends to answer the following research questions:

1. How is FoodForward South Africa's current supply chain network structured?
2. What network evolution patterns are observable in the data?
3. What potential implications may the network's evolution have on FoodForward South Africa's supply chain network design and capacity planning?

Since research on the supply chain networks of food banks in developing countries has remained relatively limited, this study intends to contribute to this area of research. FoodForward South Africa has compiled a rich dataset that connects its various supply chain partners (i.e., farmers, manufacturers, retailers, warehouses), the flow of stock (volume of food), beneficiary organisations, and their locations and time stamps of transactions. Transactional data can be analysed using complex network approaches to uncover relationships in the flow of food between supply chain partners (e.g., donors), food bank warehouses, and beneficiary organisations. FoodForward South Africa could benefit from investigating the relationship between the total number of connections in its network and the weight (i.e., the volume of food flowing between partners) of those connections when planning its strategic capacity and designing its supply chain.

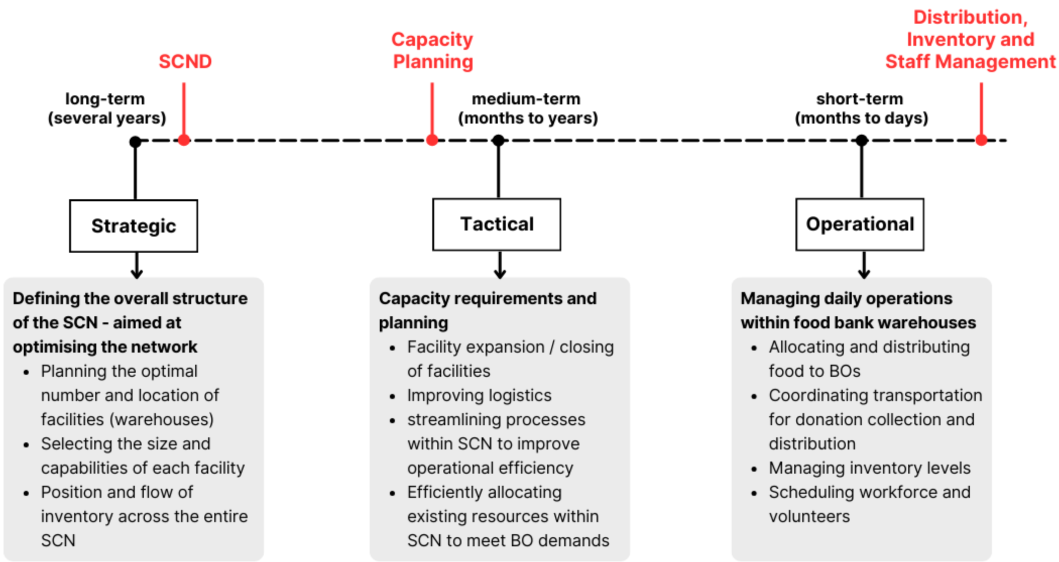

Figure 1: Planning horizon in the context of a food banking system

The remainder of this paper is organised according to the literature on food banking supply chain networks and the supply chain network design for non-profit organisations in Section 2, followed by complex network approaches. Section 3 describes the methods used in this study, including a stakeholder map and a discussion of how data was collected and processed. This is followed by an in-depth discussion of the findings in Section 4 and the conclusion and further insights in Section 5.

2. LITERATURE REVIEW

2.1. Application context: Food banking supply chains

The supply chains of food banks typically involve three stakeholders in a simplified version of the networks: donors, food banks, and beneficiary organisations [4]. As a result, these supply chains are highly complex, with multiple donors donating in-kind items (i.e., food) and money on the supply side and food banks managing the redistribution, handling, and storage of food on the demand side [6, 5]. Food banks serve as intermediaries between donors and beneficiary organisations or clusters of individuals in need, and they tend to operate out of large warehouses, managing inventory and distribution while coordinating beneficiary organisations' food requirements at different levels [8]. Unlike commercial supply chains, where demand is the primary source of uncertainty, food banks' supply chains are supply-driven and face uncertainties on the supply and demand sides [7, 5]. In addition, because they rely on donations and volunteer work, food banks operate in severely resource-constrained settings, making it even more difficult to manage operations [4, 5]. Therefore, the supply chain networks of food banks must be designed and managed effectively to maximise donations and, as a result, reach the most significant number of beneficiaries [4, 9].

Thus, a food bank's supply depends on donations from its upstream partners. The donated food products are usually surplus food or food nearing the end of its shelf lifetime that is thus not sellable but is still edible [10, 4, 5]. In addition, since donations are unpredictable in frequency, type, and quantity, it becomes increasingly difficult for food banks to manage and estimate incoming supplies [11]. On the demand side, one of the most significant difficulties is matching the specific needs of all their beneficiary organisations and individuals with their limited supply stock [12]. Therefore, it is evident that the supply chain network of food banks is becoming increasingly more complex and that new management techniques must be developed to improve these institutions' management, capacity building, and decision-making processes.

2.2. Supply chain network design for non-profit organisations

In strategic supply chain planning, the infrastructure and physical structure of the supply chain network is determined by the supply chain network design [13]. This stage is considered one of the most crucial since the configuration of a supply chain network design is proven to influence its overall performance significantly and, as a result, to impact all future tactical and operational decisions [14]. Most humanitarian relief chains are based on non-profit organisations (NPOs) that organise assistance to enhance development, reduce poverty, and improve the lives of those in need or developing nations [15, 16]. The overarching goal of these supply chains is to manage crises caused by human-made and natural disasters, such as earthquakes and tsunamis, or long-term development problems, such as hunger and malnutrition [15, 17]. These complex, highly uncertain crises occur in dynamic, highly resource-constrained contexts [15]. Therefore, the design requirements of humanitarian systems differ significantly from those of commercial supply chains because of the notable differences between the goals of non-profit and corporate organisations [18].

Most of the literature concerning non-profit supply chain design and management focuses on designing short-term relief chains that cannot be sustained in the long run owing to their lack of long-term strategic planning [18]. As a result, there is an extensive lack of literature on the supply chain network design of non-profit organisations that addresses these chronic disasters, such as access to healthcare, alleviating hunger, and access to water. Therefore, this paper aims to contribute to the existing literature on the structure and design of non-profit organisations that aim to mitigate these long-term development issues, in order to better understand the configuration and dynamics of these supply chains.

2.3. Complex network approaches

Food bank supply chains are complex, and understanding them requires a deep understanding of the networks behind them [19]. In contrast to traditional data analysis, network analysis emphasises the connections between entities rather than examining individual features to discover underlying patterns in complex systems [20]. In the mathematical literature, networks are referred to as graphs [19]. In a network (or graph), components are represented as nodes connected by links [19]. In modelling a supply chain network, nodes represent the organizations, suppliers, facilities, and customers that constitute the system [21]. The links between organizations denote exchange relationships, including different flows, such as material, information, and financial flows [22]. The links of a network can be either directed or undirected. Each connection in a directed network points from one node to another, while the links in an undirected network have no direction, as seen in Figures 2 and 3, respectively [23].

The simplest approach to represent a network is through its adjacency matrix (A), which is necessary to keep track of all its links and to provide a comprehensive network description. In a directed network, the matrix's entries (A_{ij}) are 1 if nodes *i* and *j* are connected by a link, and otherwise 0 [19]. Therefore, network links are usually represented as simple binary connections between nodes, but more complex networks may require weighted links [24]. In a weighted graph, each link is associated with a weight corresponding to the strength or importance of the relationship between two nodes [24]. Owing to its topology and quantitative information inclusion, this represents real-world systems more accurately [24]. A weighted network, as presented in Figure 4, is represented by giving each link in the adjacency matrix (w_{ij}) a value equal to the weight assigned to each link [23].

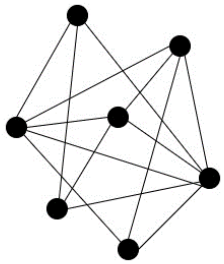

Figure 2: Undirected graph

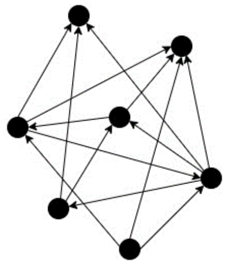

Figure 3: Directed graph

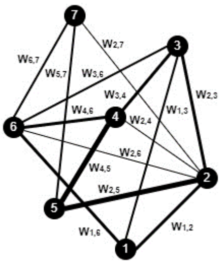

Figure 4: Weighted graph

2.4. Network measures

Network science uses a variety of metrics to analyse the structure of networks, with size (number of nodes) and density being the most essential characteristics [25]. This paper, however, mainly focuses on investigating the relationship between the total number of connections in the network and the weight computing the volume of food of those connections. Therefore, the two primary network metrics used in this study are node degree, which accounts for the directional aspect, and node strength, which accounts for the weighted aspect. Table 1 provides an overview of the various network measures employed in this study.

3. METHODS

The main processes in the methodology of this study are outlined in the flow chart in Figure 5. Before the main data collecting and processing phase, the stakeholder mapping and primary data collection process must be completed, as described in Sections 3.1 and 3.2. After that, the various network analysis steps are completed, as outlined in Section 3.3.

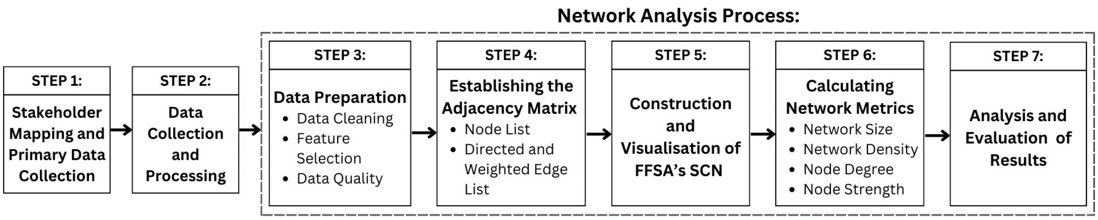

Figure 5: The methodology process followed

Table 1: Summary of the network measures employed in this study

<table>
<tr><th colspan="2">Definition:</th><th>Application to food banking networks:</th><th>Equation:</th></tr>
<tr><td colspan="4">Network density</td></tr>
<tr><td colspan="2">A network's density (ρ) is a measure of its cohesiveness and can be described as the total number of connections M relative to the total number of potential connections $N(N-1)$ [26, 25].</td><td>A network with a density of 0 is said to be entirely disconnected. In contrast, a network with a density of 1 is said to be fully connected, meaning that every node is connected to every other node [26, 25].</td><td>$\rho = M/[N(N-1)]$ (1)</td></tr>
<tr><td colspan="4">Network degree</td></tr>
<tr><td rowspan="2">Node degree indicates a node's connectivity and can be defined as the number of links connected to a node [23, 27]. Since the food bank's network can be modelled as a directed network, the in- and out-degree nodes are considered [27].</td><td><u>Node in-degree:</u> Node in-degree counts the number of incoming links to a node [23, 27].</td><td>A node's in-degree is the total number of inbound connections it has with other nodes from which it receives food.</td><td>$k_{in_i} = \sum_j a_{ji}$ (2)</td></tr>
<tr><td><u>Node out-degree:</u> Node out-degree counts the number of links flowing from a node [27].</td><td>A node's out-degree refers to the number of connections it has with other nodes through which it sends outbound food.</td><td>$k_{out_i} = \sum_j a_{ij}$ (3)</td></tr>
<tr><td colspan="4">Node strength</td></tr>
<tr><td rowspan="2">Node strength can be defined as the sum of all the link weights of each node [28]. To account for direction, the node in-strength and node out-strength are considered. In each formula, w is an element of the weighted adjacency matrix W.</td><td><u>Node in-strength:</u> Node in-strength sums the value of a node's incoming links.</td><td>The total volume of food flowing into a warehouse from suppliers (or from warehouses to beneficiary organisations) is measured by its in-strength.</td><td>$s_{in_i} = \sum_j w_{ji}$ (4)</td></tr>
<tr><td><u>Node out-strength:</u> Node out-strength sums the value of a node's outgoing links.</td><td>The total volume of food flowing from a warehouse to beneficiary organisations (or from suppliers to warehouses) is measured by its out-strength.</td><td>$s_{out_i} = \sum_j w_{ij}$ (5)</td></tr>
</table>

3.1. Stakeholders mapping

FoodForward South Africa has a warehouse located in each of the nine provinces of South Africa, where various suppliers donate food items. Various nutritionally balanced food parcels are packaged and distributed to beneficiary organisations using donated food supplies. Afterward, beneficiary organisations redistribute the food parcels as cooked meals or boxes filled with food items to various beneficiaries. For the results of the network analysis to be interpreted correctly, it is imperative to understand the dynamics of the network and the various processes occurring in the supply chain before conducting the analysis. Therefore, we also studied how warehouses manage their inventory, and distribution strategies, generate orders, and conduct transactions between supply chain entities. By conducting a stakeholder mapping and obtaining primary data directly from FoodForward South Africa, we aimed to improve our understanding of FoodForward South Africa's supply chain network structure and relationships. This would lead to more accurate results that reflect the complexities of FoodForward South Africa's supply chain network.

3.2. Data collection and processing

The data used in this paper describes how donated food items move throughout the entire supply chain network, from donors to warehouses and finally to beneficiary organisations. Food transfers from one entity to another are recorded according to the date and volume of food. Owing to data limitations, the analysis is limited to transactions that took place in 2021 and 2022. A total of 157,825 transactions were included in the data for 2021, while 256,811 transactions were included in the data for 2022. This study used features such as warehouse names, supplier codes, and beneficiary organisation codes in addition to each transaction's line weight (in kilograms).

3.3. Network analyses

FoodForward South Africa's supply chain network is populated by *N* nodes representing warehouses, suppliers, and beneficiary organisations (a BO). The links connecting the nodes are weighted based on the volume of food flows and oriented considering the flow direction, resulting in a weighted-directed network. For each year included in the study period, network analysis is used to map out the entire supply chain network based on data describing the flow of food from suppliers to warehouses and finally to beneficiary organisations. The main network analysis steps followed in this paper are outlined in the flow chart in Figure 5. For each of the years included in the study period, steps three to seven are carried out separately. These inputs are used to construct, visualise, and extract the network metrics using the R programming language. To conduct the analysis, the authors used the *igraph* R package.

4. RESULTS AND DISCUSSION

This section aims to understand better FoodForward South Africa's current supply chain network structure and design.

4.1. Network density and network size

Table 2 compares relevant characteristics (i.e., network density and size) of FoodForward South Africa's supply chain network in 2021 and 2022.

Table 2: Basic characteristics of FoodForward South Africa's supply chain network in 2021 and 2022

	2021		2022	
Total nodes	1,543 nodes	→ 9 warehouses → 131 suppliers → 1,403 BOs	2,059 nodes	→ 9 warehouses → 169 suppliers → 1,881 BOs
Total links	1,557 links	→ 150 supplier-to-WH links → 1,407 WH-to-BO links	2,077 links	→ 187 supplier-to-WH links → 1,890 WH-to-BO links
Network density	0.00065		0.00049	

The network graph for FoodForward South Africa's supply chain network in 2021 and 2022 is presented in Figures 6 and 7. In each graph, the nodes represent each supply chain entity, and the width of each link represents the weight (volume of food) flowing between entities. From these results, it is evident that the network has grown significantly since 2021. The network's total nodes increased by nearly 33.44 per cent from 2021 to 2022, and its total connections also increased by 33.39 per cent. Moreover, beneficiary organisations registered a growth of 34.07 per cent in 2022, and suppliers registered a growth of 29.01 per cent.

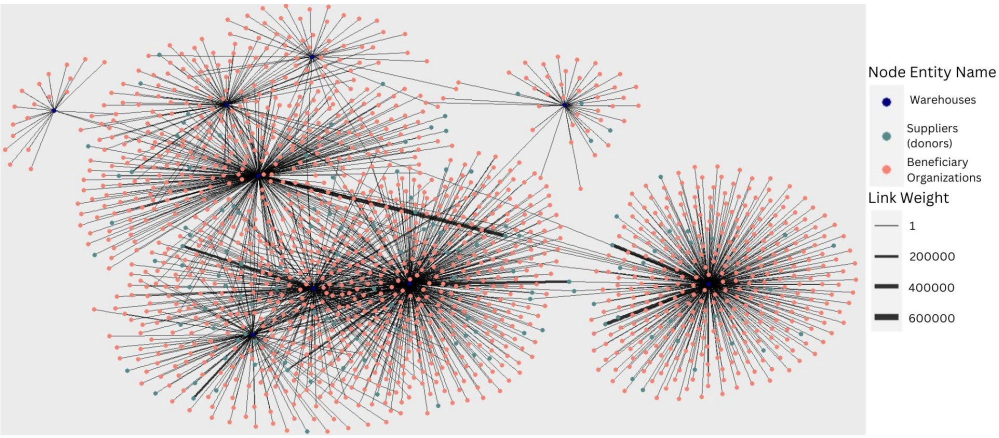

Figure 6: Network graph for FoodForward South Africa in 2021

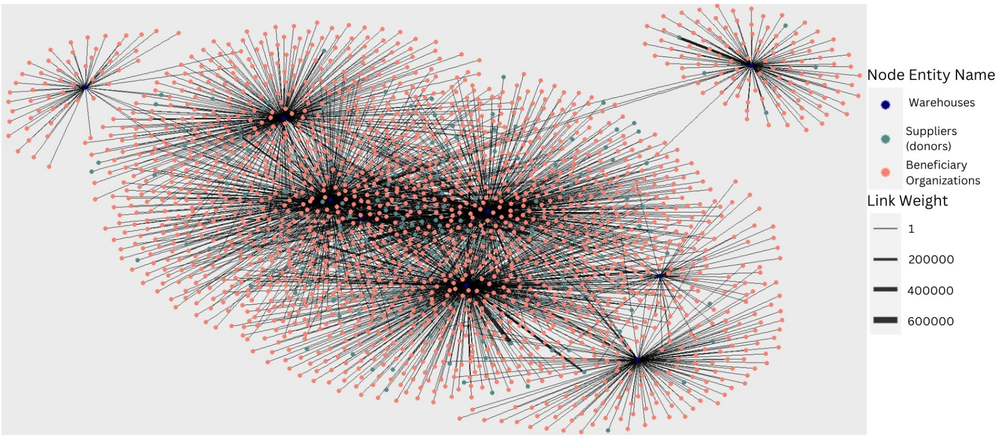

Figure 7: Network graph for FoodForward South Africa in 2022

Furthermore, the network density for each year is low, suggesting that FoodForward South Africa's network contains relatively few connections compared with the total number of possible connections. These low-density values indicate the network is fragmented, with disconnected facilities (nodes) or isolated subgroups within the graph. Since each of these isolated subgroups corresponds to one of the nine provinces in South Africa, the FoodForward South Africa network appears to be structured around the nine warehouses located in each province. This may imply that FoodForward South Africa relies on the nine provinces to build regional, short food supply chain initiatives to recover more food following this decentralised model. In addition, the data indicates no direct connections between warehouses, indicating that products are not shipped between them. However, sharing does occur between warehouses, even though these transactions are not recorded. In light of the network's expected increase in density, FoodForward South Africa would benefit from recording these transactions so that the network analysis results are unaffected.

FoodForward South Africa's network density could be augmented by increasing the connections (adding more links) among the current network entities. This could be done by recording and creating more connections between warehouses so that shipments could be sent between warehouses in different regions. Communication between warehouses may be beneficial in cases where one warehouse receives a large donation of a specific product but lacks adequate capacity to store the excess stock. Increasing FoodForward South Africa's network density could lead to better resource allocation. More suppliers are connected to warehouses, and more warehouses are connected to beneficiary organisations, making it easier to match available food to beneficiary needs. Nevertheless, the denser a network becomes, the more difficult and costly it becomes to manage its logistics, including transportation, storage, inventory management, and the redistribution of donated food.

4.2. Node degree and degree distribution

Table 3 offers an overview of the network's node degree statistics for each entity type.

Table 3: Summary of node degree statistics for each entity in 2021 and 2022

	Warehouses		Suppliers		Beneficiary organisations	
	2021	2022	2021	2022	2021	2022
Mean total degree	173	230.78	1.15	1.11	1.002	1.004
Mean in-degree	16.67	20.78	–	–	1.002	1.004
Mean out-degree	156.33	210	1.15	1.11	–	–
SD total degree	145.40	169.17	0.39	0.31	0.053	0.07
SD in-degree	15.43	22.02	–	–	0.053	0.07
SD out-degree	130.24	147.61	0.39	0.31	–	–

The warehouses, as expected, have a very high out-degree and a somewhat high in-degree. This implies that in 2021, warehouses received food from a mean of 16 different suppliers and had to distribute the food to a mean of 156 different beneficiary organisations. From the standard deviation (SD) of the warehouses' in-degree, it is evident that warehouses experience the most variation in the number of beneficiary organisations to which they distribute donated food. According to the findings from 2022, warehouses received donated food from 20 different suppliers but had to distribute it to 210 different beneficiary organisations. With more suppliers connected to a warehouse in 2022, individual donors are less likely to disrupt the network's supply side, as warehouses rely on more suppliers. However, the growing number of beneficiary organisations on the demand side, coupled with the additional suppliers, increases the complexity of the network, as food is supplied by a limited number of suppliers but distributed to a much larger number of beneficiary organisations.

Suppliers have zero incoming food and only send outgoing food to warehouses, while beneficiary organisations only accept incoming food. Therefore, suppliers' mean total degree equals their mean out-degree, and beneficiary organisations' mean total degree equals their mean in-degree. Moreover, the findings reveal that in 2021, each supplier was connected to 1.15 warehouses on average. The mean out-degree for suppliers slightly decreased to 1.11 in 2022, indicating a decline in the number of connections each supplier had with warehouses. However, each warehouse averaged four new suppliers during that time. In addition, the variation in the out-degree of suppliers reduced even further in 2022, according to the low SD values in Table 3. This suggests that warehouses establish solid connections with suppliers, resulting in suppliers remaining loyal to a specific warehouse.

Furthermore, the results in Table 3 indicate that, on average, each beneficiary organisation is connected to only one warehouse from which it receives incoming food parcels. However, there are a few exceptions where the graphs in Figures 6 and 7 clearly show beneficiary organisations receiving food from multiple warehouses. The number of beneficiary organisations that received food from two different warehouses in 2021 was four, and in 2022, the number grew to nine beneficiary organisations receiving food from two warehouses. As indicated by the low SD for beneficiary organisations, these few exceptions account for the slight variation in the node in-degree values. However, this may reflect errors in the data since FoodForward South Africa's inventory system is designed so that a beneficiary organisation may receive food from only one warehouse.

4.3. Node strength

The network's node strength statistics for each entity type are outlined in Table 4.

Table 4: Summary of node strength statistics for each entity in 2021 and 2022

	Warehouses		Suppliers		Beneficiary organisations	
	2021	2022	2021	2022	2021	2022
Mean total strength	1,663,669	2,139,071	56,814.66	56,147.28	5,367.29	5,190.19
Mean in-strength	826,968.9	1,0543,21	–	–	5,367.29	5,190.19
Mean out-strength	836,700.2	1,084,750	56,814.66	56,147.28	–	–
SD total strength	1,489,173	1,723,306	160,546.1	143,490.3	6,477.16	5,161.66
SD in-strength	829,445.3	934,938.7	–	–	6,477.16	5,161.66
SD out-strength	696,249.6	808,675.3	160,546.1	143,490.3	–	–

The mean total strength represents the average volume of food moving through each network entity type. The SD of the in-strength represents the variance in the total incoming food received by entities in the network, while the SD of the out-strength measures the variance in the total volume of food coming out of the network. As with the suppliers' node in-degree in Table 3, the suppliers' node in-degree and in-strength calculations are both zero, and the beneficiary organisations' out-degree and out-strength are also expected to be zero.

Based on Table 4, the warehouse's high mean in-strength and out-strength values indicate the network's ability to handle extremely high volumes of food. The average volume of food entering warehouses increased by 27.49 per cent from 2021 to 2022, while the average volume of food leaving warehouses increased by 29.65 per cent. Figures 8 and 9 compare the volumes of food entering (in-strength) and exiting (out-strength) each warehouse for 2021 and 2022, respectively.

According to these graphs, the amount of food supplied to FoodForward South Africa is typically lower than that to beneficiary organisations, resulting in a discrepancy between the total volume of food entering and leaving warehouses. In most cases, slight discrepancies are acceptable since donated food may not be edible at the time of donation or may have been damaged in shipment. However, significant discrepancies may suggest that FoodForward South Africa procures some food items to meet BO demands. In 2021, the discrepancy was 9,731 kg; in 2022, it was 30,429 kg, indicating a rise in food purchases made by the organisation. FoodForward South Africa's high outflow of food to beneficiary organisations compared with the inflow from suppliers may impact the supply chain network's design and efficiency. FoodForward South Africa should focus on effective inventory management and resource allocation to handle this.

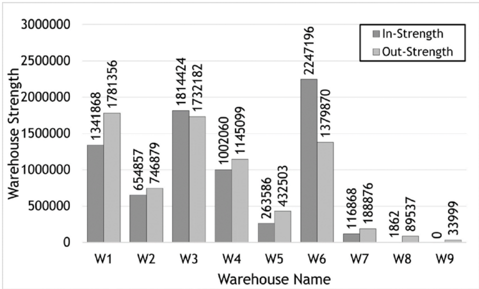

Figure 8: Warehouses' node in-strength and node out-strength in 2021

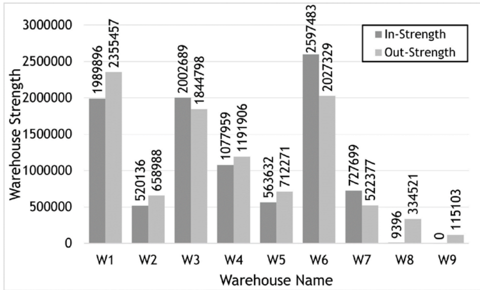

Figure 9: Warehouses' node in-strength and node out-strength in 2022

Furthermore, the high SD values attributed to the warehouses' in-strength suggest that suppliers and donations are not dispersed equally, as illustrated in Figures 7 and 8. As a result, there may be discrepancies in food availability for beneficiary organisations, with some warehouses receiving abundant supplies. In contrast, others may not supply all their beneficiaries with food. For example, W3, W6, and W7 received more food donations than they sent to beneficiary organisations, suggesting a supply imbalance in FoodForward South Africa's supply chain network. This could constrain some warehouses while others have excess space. Inter-branch transfers between warehouses are permitted in such cases since food surpluses often occur in more industrialised regions, and FoodForward South Africa has to ship to less economically active areas. On the other hand, these statistics may also indicate a mismatch between the volume of incoming donations and the demand from beneficiary organisations as a result of varying donor preferences or other distribution problems. Mismatches could negatively affect the network's efficiency and design, so identifying the root cause is crucial for planning.

On average, each supplier donated 56,815 kg of food to warehouses in 2021, as indicated in Table 4. In 2022, this value slightly decreased to 56,147 kg. This declining trend may have severe repercussions for the network's long-term design. The decreased ability of suppliers to provide food to warehouses is partly because of the weak South African economy and the fact that businesses are still recovering from the financial difficulties brought on by the COVID-19 pandemic. As a result, suppliers no longer overproduce, leaving them with limited stock to donate. Although each supplier contributed less, the total volume of incoming food increased from 2021 to 2022 as more small-scale donors participated in FoodForward South Africa's supply chain network. This has made the network more diverse and resilient, but the supply chain network's design needs to be adapted to handle a larger number of smaller donations for long-term viability.

Moreover, the findings show that each BO received an average of only 5,190 kg of food in 2022 compared with 5,367 kg in 2021 – that is, the amount of food each BO received in 2022 slightly decreased from 2021. This is likely because the number of beneficiary organisations in the network substantially increased while the amount of donated food remained relatively the same, with a slight decrease in donations. Consequently, the same amount of food had to be redistributed among a greater number of beneficiary organisations to meet the growing demand. The substantial SD values also suggest considerable variation in the volumes received by beneficiary organisations. This highlights the food bank's difficulties caused by supply shortages and balancing growing demand with limited supply.

4.4. Relationship between the warehouses' node degree and node strength

Figures 10 and 11 illustrate the relationship between node degree and node strength for each warehouse.

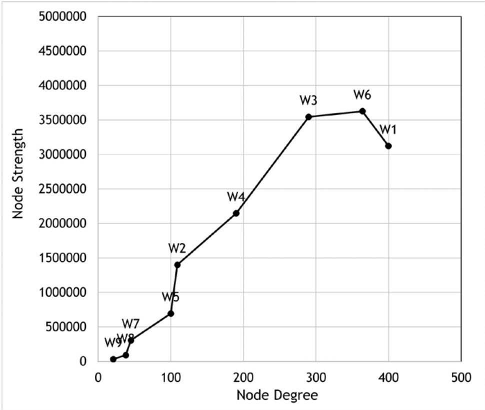

Figure 10: Node strength vs. node degree graph for all warehouses in 2021

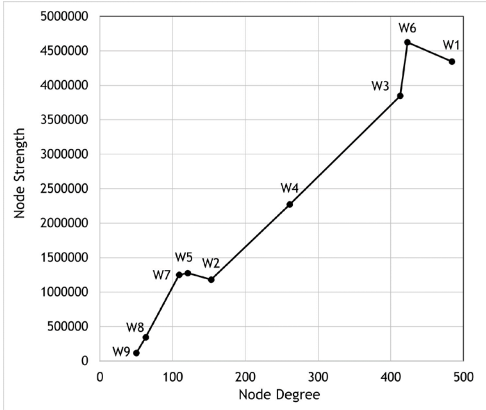

Figure 11: Node strength vs. node degree graph for all warehouses in 2022

These graphs show that the relationship between node degree and strength is not linear. Although there is a general trend for node strength to increase with node degree, that is not always the case. Warehouses with fewer connections often handle most of the food in the network. For example, W3 and W6 handle the most considerable amount of food despite having fewer connections than W1, as indicated in Figures 10 and 11. The nonlinear relationship underscores the variability in FoodForward South Africa's warehouse capacity, as some may be large hubs with immense capacity.

In contrast, others may have limited storage and distribution capacities. This relationship could help to streamline operations for optimal efficiency and effectiveness. It may, for instance, be necessary to support and optimise resource allocation for warehouses with a high node degree but a comparatively low node strength. Likewise, warehouses with high node strength but a low node degree could need scaling up or improved network integration.

Moreover, the amount of food moving through the network (node strength) is expected to increase faster than the number of new supplier and beneficiary connections formed (node degree). However, when comparing each warehouse's growth between 2021 and 2022 concerning the total degree and total strength values, as shown in Figure 12, it becomes apparent that warehouse node strength for some warehouses grows slower than the degree. For instance, from 2021 to 2022, the node degree of W2, W3, and W4 increased faster than their node strength.

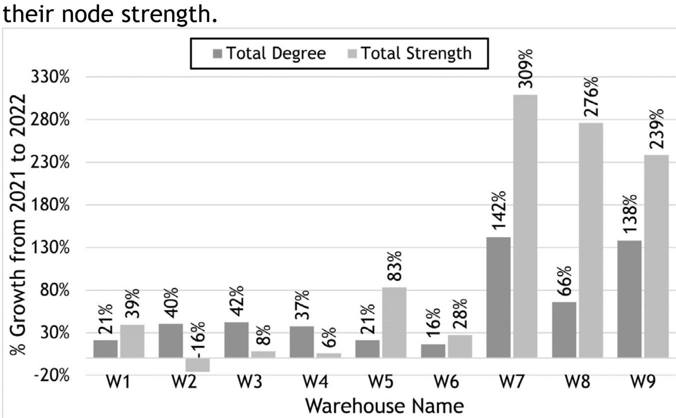

Figure 12: Comparison of each warehouse's per cent growth between 2021 and 2022 in respect of total degree and total strength

In 2022, W2 received less donated food because it was connected to fewer suppliers, resulting in decreased in-strength, out-strength, and in-degree values. In other words, the warehouse's demand increased, resulting in each BO receiving substantially less food. This would significantly impact the design of FoodForward South Africa's supply chain network since the volume of food remains essentially the same. Yet, the handling costs associated with repackaging the donated food for more beneficiary organisations would increase considerably. Similarly, W4 showed an overall decline in suppliers, yet the volume of incoming and outgoing food increased slightly from 2021 to 2022. Therefore, although W4 had roughly 19 per cent fewer suppliers in 2022, the amount of food donated still increased, suggesting that this warehouse's suppliers donated significantly more food in 2022. In addition, despite serving 44 per cent more beneficiary organisations in 2022, W4 provided each BO with more food than in 2021, indicating an expansion in its distribution and storage capabilities.

In contrast, W2 showed a significant increase in suppliers and beneficiary organisations, but did not expand its capacity accordingly. This would pressure the warehouse's limited resources, reducing the amount of food available to beneficiary organisations and increasing the risk of food waste. Consequently, FoodForward South Africa must plan to increase the warehouse's resources, infrastructure, and partnerships to maintain this rapid growth in node degree at W2. In addition, Table 5 shows that most warehouses had increased degree and strength metrics over the two years. Among them, W7 had the most significant growth, with a 573 per cent increase in the volume of food it received from suppliers.

Table 5: Comparison of each warehouse's growth between 2021 and 2022 regarding degree and strength values

	In-degree	Out-degree	Total degree	In-strength	Out-strength	Total Strength
W1	50% increase	18% increase	21% increase	48% increase	32% increase	39% increase
W2	36% decrease	52% increase	40% increase	21% decrease	12% decrease	16% decrease
W3	40% increase	43% increase	42% increase	10% increase	7% increase	8% increase
W4	19% decrease	44% increase	37% increase	8% increase	4% increase	6% increase
W5	25% increase	21% increase	21% increase	114% increase	65% increase	83% increase
W6	26% increase	15% increase	16% increase	16% increase	47% increase	28% increase
W7	60% increase	153% increase	142% increase	523% increase	177% increase	309% increase
W8	100% increase	65% increase	66% increase	405% increase	274% increase	276% increase
W9	0% (no growth)	138% increase	138% increase	0% (no growth)	239% increase	239% increase

5. CONCLUSION

This study evaluated the transactions recorded in 2021 and 2022 for FoodForward South Africa to characterise the entire supply chain network. According to the data, beneficiary organisations grew by nearly 34.07 per cent over those two years, and suppliers grew by 29.01 per cent. Despite this positive growth rate, it is also observed that the logistics and coordination of the supply chain network become more complex as more beneficiary organisations connect on the demand side along with the additional suppliers on the supply side. The network's range of suppliers also diversified throughout the study period, increasing its resilience amid disruptions and shortages brought on by individual donors. In addition, it is crucial to consider the possibility of averaging errors that may occur owing to the hub-and-spoke nature of the model when analysing the network model's results.

It also becomes apparent from the analysis that the number of moving parts of the system is increasing (more handling), although the volume of food flowing through the network does not increase as much. This growth pattern leads to a supply-demand imbalance, necessitating consideration of alternatives to the current supply chain network design. Furthermore, the nonlinear relationship between node degree and strength underscores the variability in the demonstrated capacity of FoodForward South Africa's warehouses, indicating that supplies are not dispersed equally among them. There may be discrepancies in food availability for beneficiary organisations, with some warehouses receiving an abundance of supplies while others may not be able to supply all their beneficiaries with food.

It is crucial to consider that the reference period of 2021 and 2022 coincided with the peak of the COVID-19 pandemic, which might have affected the analysis and skewed the data. Therefore, it is recommended that data from subsequent years be analysed better to understand the evolution of the supply chain network as the world emerges from the COVID-19 pandemic. In addition, comparing one year with another may lead to distortions in the growth measure. It is advised that these shortcomings be addressed in future research.

The analysis also reveals opportunities for optimisation. The network models that have been generated provide valuable insights into the supply chain network's structure. Therefore, future research should explore ways to leverage these models in order to optimise different parts of the supply chain network, thereby enhancing its efficiency under different circumstances.

REFERENCES

[1] UNEP, "United Nations Environment Programme food waste index report 2021," available at https://www.unep.org/resources/report/unep-food-waste-index-report-2021 (Accessed on 28 August 2024).

[2] W. S. Africa, "Food loss and waste: Facts and futures," WWF South Africa, 2017 available at https://www.wwf.org.za/?21641/Food-Loss-and-Waste-Facts-and-Futures-Report (Accessed on 26 August 2024).

[3] Stats SA, "Measuring food security in South Africa: Applying the food insecurity experience scale," Department of Statistics South Africa, 2021.

[4] C. Martins, M. Melo, and M. Pato, "Redesigning a food bank supply chain network in a triple bottom line context," *International Journal of Production Economics,* vol. 214, pp. 234-247, 2019.

[5] A. F. Rivera, N. R. Smith and A. Ruiz, "A systematic literature review of food banks' supply chain operations with a focus on optimisation models," *Journal of Humanitarian Logistics and Supply Chain Management,* vol. 13, pp. 10-25, 2023.

[6] C. Ataseven, A. Nair and M. Ferguson, "The role of supply chain integration in strengthening the performance of not-for-profit organisations: Evidence from the food banking industry," *Journal of Humanitarian Logistics and Supply Chain Management,* vol. 10, no. 2, pp. 101-123, 2020.

[7] M. Kaviyani-Charati, M. Ameli, F. H. Souraki and A. Jabbarzadeh, "Sustainable network design for a non-profit food bank supply chain with a heterogeneous fleet under uncertainty," *Computers & Industrial Engineering,* vol. 171, 108442, 2022.

[8] A. P. Marla, M. Laurie, K. Chen-Yu and M. Alex, "Accountability and relationship-definition among food banks partnerships," *VOLUNTAS: International Journal of Voluntary and Non-profit Organizations,* vol. 31, no. 5, pp. 923-937, 2019.

[9] P. L. González-Torre and J. Coque, "How is a food bank managed? Different profiles in Spain," *Agriculture and Human Values,* vol. 33, no. 1, pp. 89-100, 2015.

[10] M. S. Wetherill, K. C. White, C. Rivera and H. K. Seligman, "Challenges and opportunities to increasing fruit and vegetable distribution through the US charitable feeding network: Increasing food systems recovery of edible fresh produce to build healthy food access," *Journal of Hunger & Environmental Nutrition,* vol. 14, no. 5, pp. 593-612, 2018.

[11] F. Alkaabneh, A. Diabat and H. O. Gao, "A unified framework for efficient, effective, and fair resource allocation by food banks using an approximate dynamic programming approach," *Omega,* vol. 100, 102300, 2021.

[12] R. Akkerman, M. Buisman, F. Cruijssen, S. de Leeuw and R. Haijema, "Dealing with donations: Supply chain management challenges for food banks," *International Journal of Production Economics,* vol. 262, 108926, 2023.

[13] K. Govindan, M. Fattahi and E. Keyvanshokooh, "Supply chain network design under uncertainty: A comprehensive review and future research directions," *European Journal of Operational Research,* vol. 263, no. 1, pp. 108-141, 2017.
[14] R. Z. Farahani, S. Rezapour, T. Drezner and S. Fallah, "Competitive supply chain network design: An overview of classifications, models, solution techniques and applications," *Omega,* vol. 45, pp. 92-118, 2014.
[15] M. Çelik, Ö. Ergun, B. Johnson, P. Keskinocak, Á. Lorca, P. Pekgün and J. Swann, "Humanitarian logistics," in *2012 Tutorials in Operations Research*, INFORMS, 2012, pp. 18-49.
[16] N. Dubey and A. Tanksale, "A study of barriers for adoption and growth of food banks in India using hybrid DEMATEL and analytic network process," *Socio-Economic Planning Sciences,* vol. 79, 101124, 2021.
[17] R. E. Overstreet, D. Hall, J. B. Hanna and R. K. Rainer, "Research in humanitarian logistics," *Journal of Humanitarian Logistics and Supply Chain Management,* vol. 1, no. 2, pp. 114-131, 2011.
[18] S. Bhattacharya, S. Hasija and L. N. van Wassenhove, "Designing efficient infrastructural investment and asset transfer mechanisms in humanitarian supply chains," *Production and Operations Management,* vol. 23, no. 9, pp. 1511-1521, 2014.
[19] A.L. Barabási, "Network science," *Philosophical Transactions of The Royal Society A: Mathematical*," Physical and Engineering Sciences, 371, 20120375, 2013.
[20] C. A. R. Pinheiro, *Network science: Analysis and optimization algorithms for real-world applications*, John Wiley & Sons, 2022.
[21] M. A. Bellamy and R. C. Basole, "Network analysis of supply chain systems: A systematic review and future research," *Systems Engineering,* vol. 16, no. 2, pp. 235-249, 2012.
[22] E. J. S. Hearnshaw and M. M. J. Wilson, "A complex network approach to supply chain network theory," *International Journal of Operations & Production Management,* vol. 33, no. 4, pp. 442-469, 2013.
[23] M. Newman, *Networks: An introduction*, Oxford University Press, 2010.
[24] B. Katy, S. Soma and V. Alessandro, "Network science," *Annual Review of Information Science & Technology,* vol. 41, pp. 537-607, 2007.
[25] S. A. Trivette, "The importance of food retailers: Applying network analysis techniques to the study of local food systems," *Agriculture and Human Values,* vol. 36, pp. 77-90, 2019.
[26] Y. Kim, T. Y. Choi, T. Yan and K. Dooley, "Structural investigation of supply networks: A social network analysis approach," *Journal of Operations Management,* vol. 29, no. 3, pp. 194-211, 2011.
[27] X. Lin, Q. Dang and M. Konar, "A network analysis of food flows within the United States of America," *Environmental Science & Technology,* vol. 48, no. 10, pp. 5439-5447, 2014.
[28] M. Sartori and S. Schiavo, "Connected we stand: A network perspective on trade and global food security," *Food Policy,* vol. 57, pp. 114-127, 2015.