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Research article

Supply chain dynamics beyond optimization: Metabolism of regional inter-firm networks

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ABSTRACT

Sustainable supply chain networks are critical to the survival of companies in interconnected business ecosystems. Today's rapidly changing market conditions require firms to restructure their network resources flexibly. In this study, we quantitatively investigated how firms' ability to adapt to the turbulent market depends on the stable maintenance and flexible recombination of inter-firm relationships. Using the proposed quantitative index "metabolism," we measured the micro-level dynamics of the supply chain, which represents each firm's average replacement rate of business partners. We applied this index to longitudinal data on the annual transactions of about 10,000 firms from 2007 to 2016 in the Tohoku region, which was affected by the 2011 earthquake and tsunami. The distribution of metabolism values differed across regions and industries, indicating differences in the adaptive capacity of the corresponding firms. We also found the typical balance between supply chain flexibility and stability for successful companies that have survived in the market for a long time. In other words, the relationship between metabolism and duration was not linear but U-shaped, indicating an appropriate metabolism value for survival. These findings provide a deeper understanding of supply chain strategies for adapting to regional market dynamics.

1. Introduction

Analysing the market environment and optimising business relationships has long been a top priority for companies. Familiar strategies have been to select optimal locations that reduce production costs and to strengthen relationships with specialised suppliers that meet strict order requirements and product specifications. Through location optimisation, companies have benefited from low-cost manufacturing in developing countries or rural areas, favouring geographically dispersed production. Through order optimisation, companies have built solid mutual trust and minimised inventories through a tightly controlled system such as just-in-time operations. Accompanied by the rapid development of Internet technologies that enabled remote and fine-tuned operations, these supply chain strategies were effective when market conditions were mostly stable.

However, the selection and concentration of the most advantageous business partners proved vulnerable to unforeseen market fluctuations. The COVID-19 pandemic and subsequent national responses, such as the proliferation of under-declared states of emergency, factory closures due to falling consumption, and the slowing of international logistics due to transport delays, have led to unexpected supply chain disruptions. In the face of these disruptions, more people are becoming aware of the globally connected

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reality of business relationships and the risks of being disconnected. Many countries have decided to return to domestic production, offering financial support for reshoring and inshoring of production capacity [1]. Many companies have begun to rethink their operations, recognising the need to decentralise and diversify in order to build resilient supply networks. In the crisis, offshoring and specialisation proved to be a source of vulnerability, particularly in supply chains where substitution was difficult [2]. Global value chain risks have existed for more than a decade as a result of prioritising efficiency and low cost over sustainability and resilience [3]. However, the pandemic has reminded us of the risks of unexpected disruptions and the need to prepare for risks beyond local optimisation in normal situations [4].

This paper proposes a new quantitative index to analyse the dynamics of interrelationships among Japanese firms. Based on a large amount of transaction data, we calculated the exchange rates of firms' business transactions as an index of metabolism. We examined this index to see whether it: (1) reflected changes in industrial structure, (2) correlated with firm performance, such as business life in the regional economy, (3) captured the evolution of the regional cluster in Tohoku, where the risk of unexpected disruptions had become apparent. In the following section, we review how firm linkages have been evaluated theoretically and empirically from the perspective of network dynamics.

1.1. The impact of supply chain flexibility and agility

The network resource theory considers the links between firms as resources as a knowledge medium [5,6]. Analysis of the resource profiles of partner firms in inter-firm alliances revealed that firm performance differs depending on the characteristics of its partner firms [7,8]. Analysis of how interconnected firms extract value from each other's resources revealed that competitive advantage comes not only from internal resources [9,10] but also from the complementarity of resources among firms [6]. However, this does not mean that stronger ties with homogeneous partners lead to more innovation [11,12]. While many studies suggest that close and long-term relationships with other firms lead to the benefits of fostering trust [13–15], too much embeddedness within the network would lead to rigidity, making it difficult to drive innovation [14]. Overly strong and cohesive networks are prone to rigidity and dysfunctional phenomena that make innovation difficult, such as vertically integrated large firms with resistance to reforming business relationships in response to market changes [16]. Therefore, if the benefits of enhanced inter-firm communication and local government support in industrial clusters are too strong, they can lead to rigid specialisation or socio-economic lock-in, which can be an obstacle to innovation [17].

As knowledge becomes more specialized and diversified, loosely coupled networks that provide external knowledge become more important, especially in multi-technology companies that deal with a large number of technologies and need more knowledge to cope with uneven developments [18–20]. Competitive pressures reduce the stages of hierarchical structures in the market, triggering the search for new cooperative relationships and the redefinition of organizational boundaries. Specializing in technological updates to a firm's area of expertise while receiving technology and knowledge from the outside enables keeping a state-of-the-art technological level [21].

Many studies have pointed out that supply chain flexibility and agility have a positive impact on firm performance, such as growth, market share, and technology exploration and deepening [22–26]. Agile supply chains outperform less astute competitors in a turbulent business environment [27–30]. The more a company's supply chain is agile, the faster it can recover from a disaster and improve its performance [31]. By incorporating network redundancy and flexibility into the supply chain that allows for alternative trading partners, firms can achieve rapid resilience [32].

1.2. Balance between weak and strong ties

Strong ties do not always guarantee that many innovations will emerge [33]. In fact, when constructing business strategies in inter-firm networks, it is necessary to pay attention to the balance between weak and strong ties [34,35,13,36]. While networking with weak ties has been reported to increase business opportunities, there is a risk for entrepreneurs with low social skills of becoming too embedded and locked into their close social ties [37]. Dynamic capability is a firm-specific ability to integrate, build and reconfigure internal and external capabilities to respond to a changing environment. It focuses on the dynamic process of renewing innovative competitive advantages according to the firm's market position and the path dependencies of the development stage of its capabilities and resources [38].

The positive effect of network embedding on firm survival is reversed beyond a certain threshold [16]. March showed that there is an optimal balance between exploration and exploitation in organisational learning, demonstrating that while exploitation brings short-term benefits, firms that do not engage in exploration are likely to fail in the face of change [35]. It is also relevant to the concept of ambidextrous management, which simultaneously achieves incremental and discontinuous innovation by incorporating activities [39]. However, the difficulty in striking a balance between exploration and exploitation lies in the fact that firms tend to choose exploitation, which offers greater certainty of short-term success. Exploration is inefficient and tends to increase the number of poorly stratified ideas. However, without exploration efforts, the likelihood of failing to adapt to a changing business environment increases [40].

1.3. Necessity of measuring network dynamics

Previous studies have shown that the dynamics of inter-firm networks is one of the most critical factors in bringing about innovation, both by strengthening existing transactions and by establishing new linkages. However, a recent review of the relevant

Table 1
Number of firms with ten or more average transactions in Tohoku region.

Year	Tohoku	Aomori	Akita	Iwate	Yamagata	Fukushima	Miyagi
2007	9,710	999	1,063	1,301	1,767	2,144	2,381
2008	9,583	984	1,049	1,288	1,745	2,087	2,366
2009	9,483	967	1,028	1,276	1,738	2,063	2,346
2010	9,391	954	1,022	1,262	1,718	2,039	2,338
2011	9,276	945	999	1,251	1,704	2,023	2,303
2012	9,225	942	993	1,246	1,689	2,013	2,300
2013	9,175	929	977	1,240	1,685	2,008	2,293
2014	9,082	921	964	1,237	1,668	1,988	2,268
2015	9,003	918	959	1,224	1,645	1,961	2,261
2016	8,955	914	951	1,209	1,639	1,951	2,257

[1] Courtesy of Tokyo Shoko Research, Inc.

literature shows that few studies have quantitatively examined micro-level dynamics based on large-scale data, compared to the accumulation of theoretical studies and empirical analyses [31,41–44]. Laaksonen conducted a literature review of papers on dynamic capabilities and found that studies discussing empirical issues have received less attention than the findings of studies identifying conceptual issues. He concluded that it is essential for researchers to overcome theoretical ambiguities by shedding light on the quantitative measurement methods needed for empirical studies [42]. Brozovic reviews the literature on strategic flexibility, defined as the ability to respond to change, and finds progress in the field, ranging from a relative scarcity of contributions and the prominence of conceptual studies to a significant increase in empirical research and the importance of quantitative studies [43]. A similar trend can be observed in a recent literature review on supply chains, which reveals that the majority of studies are qualitative, focusing on conceptual and theoretical developments, with a lack of studies based on verifiable measurements [45,31,41,44].

1.4. Quantitative analysis of large-scale inter-firm networks

Inter-firm transaction networks are one of the most comprehensive and reliable datasets for capturing relationships between firms. In addition to their functionality as supply chains for the exchange of money and goods, they serve as channels for the exchange of value, information and knowledge, indicating cooperative and trusting relationships. With the recent availability of high-quality, large-scale firm data in Japan, quantitative analyses of inter-firm networks have been conducted using existing network indicators and numerical simulation models [46–51]. Among these studies inspired by biological models, a node indicator and node classification method designed using structural information of bacterial metabolic networks [52] was applied to the evaluation of firms in an inter-firm trade network, and firms with more links to different clusters were found to have the ability to enhance the small-world property of the regional network [46]. However, these studies analysed the static network structure of inter-firm transactions at one point in time. They did not capture the dynamics of how the process of firms' environmental adaptation and economic activities lead to the development of local industries.

Using data on inter-firm transactions, we propose the concept and calculation method of "metabolism" of firms, defined on the basis of the replacement rate of inter-firm transactions. As a result of multiple comparison tests, the average duration of firms showed statistically significant differences according to their metabolism level. The result suggests that both firms with highly fixed and fluctuating business relationships had difficulty surviving on the business market. By analysing the location of Changers and Holders based on their metabolism, we also found that the regional cluster activated by government reconstruction projects had a high metabolism, indicating its potential to incorporate new business opportunities. The findings provide a new understanding of supply chain strategy and policy to develop firm competence to adapt to regional market dynamics.

2. Methods

2.1. Data set

The data from Tokyo Shoko Research's (TSR) commercial business databases include business transactions and firm attributes for ten years from 2007 to 2016. We focused on firms with ten or more average business transactions, resulting in a total of about 10,000 firms per year (Table 1). In the dataset, there are many small firms with a small number of business partners who rarely change their partners. Therefore, we excluded these small firms from our experiment and focused on firms with ten or more average partners, which did not have a major impact on the similarity of their partners (Fig. A.8, A.9). Each company's business partners were classified in the TSR dataset as suppliers, customers and shareholders. We excluded shareholders from the dataset, as our focus is on the dynamics of business transactions between suppliers and customers. We also excluded companies that existed for only one year because we used transaction data for at least two consecutive years, as described in our experimental settings.

We created a network with companies as nodes and transactions between companies as edges. The data have up to 20 suppliers and customers for each firm, meaning that each firm can report links up to a maximum of 40 business partners. In the inter-firm network, large enterprises have more links than they report because they are more likely to be reported by other smaller enterprises, which regard large enterprises as their main partners. Therefore, limiting the number of links allows us to extract the essential features of the networks associated with the Tohoku region, rather than the entire business network. The network was unweighted

Table 2
Descriptive statics of the firm features.

Features	count	mean	std	min	max
Sales growth	11,342	106.213	76.930	27.333	6,711.667
Age	11,342	38.345	15.754	0.000	118.000
Plants	11,342	2.105	12.581	0.000	771.909
Employees	11,342	46.685	197.898	1.000	12,082.820
Sales	11,342	2.11E+06	2.01E+07	2.40E+03	1.64E+09
Transactions	11,342	13.725	3.397	10.000	43.200
Duration	11,342	9.130	2.063	2.000	10.000

and undirected, as the data did not include the monetary value of flows between firms. As a pre-processing step, duplicate edges and self-loops were removed for each year. To investigate the impact of the supply chain disruption caused by the Great East Japan Earthquake in 2011, we included firms in the analysis data if at least one of the two firms with a business relationship was located in the affected area of the Tohoku region (Aomori, Iwate, Miyagi, Akita, Yamagata and Fukuoka prefectures). Companies located outside the Tohoku region that had business relationships with Tohoku companies were included in the total number of companies shown in the “Tohoku” column of Table 1. Thus, the total number of firms in the six prefectures of Tohoku is less than the number of firms in the “Tohoku” column in each year.

Historically, Tohoku has been one of the least industrialised regions in Japan. As the Japanese government attaches great importance to the development of locally balanced industry and environmental protection, large companies have relocated mass production facilities to local regions such as Tohoku without regard for the diversity and heterogeneity of each region. The Industrial Relocation Promotion Law was enacted in 1972 to promote the relocation of factories from urban areas with excessive industrial concentration to local areas with low industrial concentration and low land prices. The aim was to stimulate the regional economy and reduce income disparities through relocation, accompanied by the construction of new and additional factories. After the extension of the Tohoku Expressway in 1982, relocation accelerated and industrial clusters developed in the Tohoku region. Most of the newly established factories were transplants of manufacturing industries without research and development departments, controlled by headquarters in Tokyo. As a result, the industrial structure in the Tohoku region at that time involved vertical links with Tokyo rather than links with the local community. Following the expansion of the factory base, horizontal transactions within the region are gradually increasing. However, even now the functions of business planning and R&D in the region are weak. In addition to the weakness of local network construction, the regional economy in Tohoku was severely affected by the Great East Japan Earthquake in 2011. More than half of Japanese companies dispersed their suppliers, directly or indirectly affected by the supply chain disruption in Tohoku. Following the disaster, the Japanese government invested a massive reconstruction budget in the affected areas. Government support for post-disaster recovery focused on regional groups of companies trying to rebuild fragmented networks.

To investigate the dynamics of business transaction networks in the Tohoku region, we designed seven features using the firm data shown in Table 2 and two features of industry and region, excluding from the analysis attributes with few registered data. Among the features, age was the age of the firm, calculated as the last year of the experimental period in 2016 minus the year of establishment. As the categorical features of region and industry were converted to numerical values and their values have no meaning, only their names and the number of data are given in the table. We treated it as separate data if a firm moved to another region or changed its industry category during the experimental period. For the other numerical characteristics that had different values in each year, such as sales and transactions, we used average values for each firm. We excluded firms with missing characteristics, leaving 11,342 firms for analysis. Fig. 1 summarises the steps and methods we used to analyse the dynamics of each firm’s business partners in the supply chain network.

2.2. Definition

This paper introduces a basic concept of metabolism based on inter-firm transactions, shown in Fig. 2. The central circle represents the target company, and the surrounding circles represent the target company’s business partners. The colour transitions of the surrounding circles indicate the annual turnover of the business partners, and the thickness of the line connecting the centre circle and the surrounding circle indicates the duration of the transaction. We assumed that a company survives in the regional economic ecosystem by replacing some of its business partners, just as a living organism maintains its life through metabolism by decomposing and recomposing its components to a certain extent. We therefore hypothesised that there is an optimal value of metabolism for each company, according to the given market conditions.

2.2.1. Metabolism

Metabolism is an indicator of how many transactions a company has replaced in a given period, defined as transaction continuity minus one. Transaction continuity is an indicator of how long a company’s inter-firm transactions have lasted and is calculated as the average of the similarity of the companies with which the company has transactions over two consecutive years. As most business relationships tend to continue from one year to the next and our focus is on how business relationships have changed, we used the similarity measure of Jaccard coefficients, where the denominator is the union of the target company’s business partners in two consecutive years. We defined metabolism using the following equation (1),

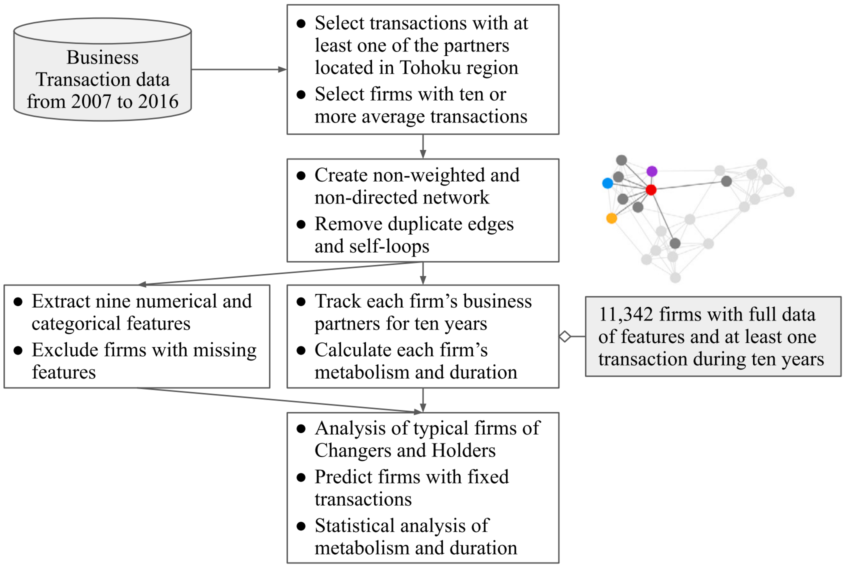

Fig. 1. Flow chart summarizing the steps and methods we used to analyze the dynamics of each firm's business partners.

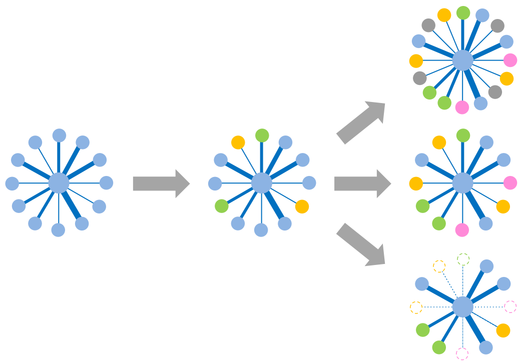

Fig. 2. Conceptual representation of metabolism based on inter-firm transactions. The colour transitions of the surrounding circles represent the replacement of the business partners of the target company in the central circle. The widths of the links between the circles indicate the duration of the transactions. Three patterns of increasing metabolism are shown: increase, replacement and decrease of business partners.

$$Metabolism = 1 - \frac{1}{n}\sum_{y=y_1}^{y_n}\frac{T_y \cap T_{y+1}}{T_y \cup T_{y+1}} \quad (1)$$

where n is the years of the dataset period minus 1, and T_y, T_{y+1} represents the partner enterprises of the target enterprise in two consecutive years of $y, y+1$. For example, if the data set period is five years, n in equation (3.1) is set to 4 in order to calculate the similarity between the previous and subsequent years. If a company does not change its business partners, its metabolism is 0; if it replaces all its partners, its metabolism is 1. Suppose a company does not have any business partners in the year before or after the period of interest. In this case, the level of metabolism cannot be calculated, which leads to the following definition of duration.

2.2.2. Duration

Although the number of years a firm has been in business is usually determined from information such as bankruptcies and closures, such information is often difficult to obtain in advance and is not sufficient for quantitative analysis. In contrast, we used explicitly available firm transaction data to estimate duration based on the number of years a firm has at least one counterparty in the dataset. This corresponds to the assumption that even if a target enterprise did not report its data for a certain year, it is still considered to exist as long as it has at least one enterprise listed as a customer or supplier. Conversely, even if none of the enterprises report the enterprise as a business partner, the enterprise is still considered to exist if it reports at least one link with the other enterprise.

2.2.3. Changers and Holders

As described in the results, the metabolism rate showed a skewed distribution, with the majority of firms having a metabolism rate close to the median. Within the companies that have been in the experiment for a maximum of ten years, we define "Changers" and

Table 3
Number of firms and basic statistics by quantile of metabolism.

Quantile	Firms	Average	Median	Standard deviation
2.5	510	0.000	0.000	0.000
5	506	0.018	0.019	0.006
10	1530	0.044	0.044	0.010
25	2547	0.082	0.082	0.013
50	2548	0.135	0.134	0.018
75	1529	0.202	0.200	0.022
90	509	0.273	0.270	0.017
95	255	0.334	0.333	0.017
97.5	254	0.456	0.430	0.087

"Holders" as companies that belong to the top 2.5% and the bottom 2.5% of the metabolism, respectively. Since firms with extremely high or low metabolisms tend to have shorter durations, Changers and Holders are rare among firms with the same metabolism level.

2.3. Measuring the impact of counterparty substitution

2.3.1. Predicting firms with fixed transactions

As a preliminary analysis of the effect of partner replacement, we focused on firms with completely unchanged transactions throughout their existing years in the dataset. We considered partner fixation as a binary classification problem to separate firms with zero metabolism from the others. Based on the previous work that used a large set of customer-supplier relationship features in business data mining [49], we applied logistic regression to predict firms with fixed relationships. Although there are other advanced machine learning approaches to solving classification problems, we used the traditional method because our research objective is not to improve the accuracy of the prediction, but to evaluate the relative importance of the features on the prediction.

We conducted the first experiment using the existing 11,342 firms in our dataset. Within the data set, 502 firms had completely fixed transactions with zero metabolisms, and 10,840 firms had changed at least one customer-supplier relationship during their existence with more than zero metabolisms. We used the firms with zero metabolisms as negative instances. As positive instances, we randomly selected the same number of firms with more than zero metabolisms. We created five sets of training data with five different sets of positive instances and used 70% of each set as training data and the rest as test data. With the data set, we compared the performance of the following learners using fivefold cross-validation with L2 parameter for regularisation. We used precision, recall and F1 score as performance measures and regression coefficients to evaluate the importance of the features.

For statistical analysis, we used VIFs to investigate multicollinearity and to confirm that all features were applicable to the analysis (Appendix A.9). We performed logistic regression to test the statistical significance of the features using one of the datasets with model selection techniques of stepwise regression (Appendix A.10).

2.3.2. Assessing groups with different metabolisms

We then performed multiple comparison tests to determine if there were significant differences in the duration of the groups of companies divided by metabolism level. According to metabolism, we divided the data into nine quantiles separated by 2.5%, 5% and 10% for both quantile and upper and lower quantiles. The basic statistics for each quantile are shown in the Table 3.

To determine which of the groups had the significant difference, we analysed whether there was a difference in mean duration between the groups. To avoid the problem of multiplicity, where the significance level rises above an assumed value when the test is repeated many times on two groups, we used the Tukey-Kramer method [53,54]. This is a typical multiple comparison test that takes into account the maximum difference between several groups of different sizes. The statistical test quantity $max.t$ for the number of groups m is expressed by the following formula (2), (3), (4),

$$max.t = \frac{max|\bar{X}_i - \bar{X}_j|}{v\sqrt{\frac{1}{n_i} + \frac{1}{n_j}}}, \tag{2}$$

$$v = \sqrt{\frac{\sum_{i=1}^{m} u_i}{\sum_{i=1}^{m}(n_i - 1)}}, \tag{3}$$

$$u_i^2 = \frac{\sum_{k=1}^{n_i}(x_k - \bar{X}_i)^2}{n_i - 1} \tag{4}$$

where u_i^2 is the sum of squares of group i with sample size n_i and group means $\bar{X}_i$, and v is the unbiased standard deviation of the sum of squares for group m, divided by the sum of degrees of freedom for group m, and rooted. The numerator of $max.t$ is the most significant difference between the two sample means $\bar{X}_i, \bar{X}_j$. A difference between two groups is considered significant if it falls within the 5% significance level of the distribution of $max.t$ values.

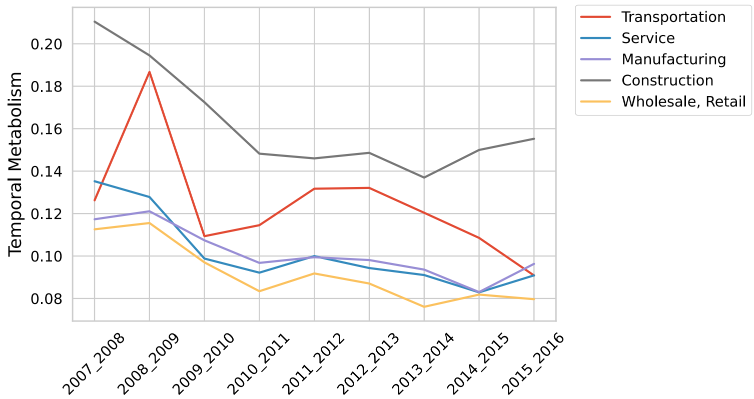

Fig. 3. Transition in the temporal metabolism of firms in five main industries. The temporal metabolism tended to increase after the large exogenous shocks in 2008 and 2011.

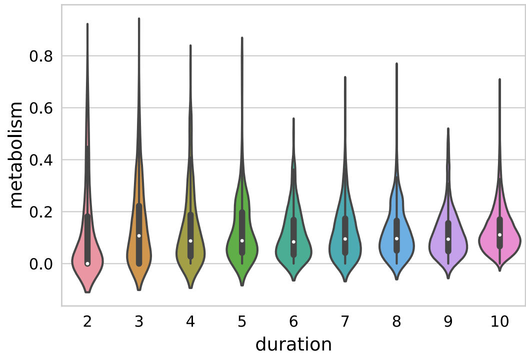

Fig. 4. Distribution of metabolism and duration of firms in the Tohoku region. Firms with shorter duration tended to have lower metabolism, and the variance of their metabolism tended to be larger than that of firms with longer duration.

3. Results

3.1. Basic characteristics of the metabolism

3.1.1. Impact of exogenous shocks on business relationships

First, we examined the transition of temporal metabolism, calculated by one minus the Jaccard similarity of each firm's business partners between two consecutive years in five major industries (Fig. 3). Overall, temporal metabolism tended to increase or decrease more slowly in the year following large exogenous shocks, such as the Lehman shock in 2008 and the Great East Japan Earthquake in 2011. Wholesale and retail trade had the lowest temporal metabolism and construction the highest, and the order did not change over the experimental period of ten years.

3.1.2. Relation between metabolism and duration

Fig. 4 shows the distribution of metabolism by duration among 11,342 firms with ten or more average transactions in the Tohoku region. Firms with a duration of one year were excluded from the sample, as metabolism is calculated based on the business relationship between at least two consecutive years. Although the number of firms was similar in size except for firms with a ten-year duration (Appendix Table A.8), the distribution of metabolism varied widely among firms according to their duration. The variance of metabolism tended to be larger when the duration was short, and the median of metabolism in each duration tended to be higher as the duration increased. The number of companies divided by 15 different ranges of metabolism for each duration shows a similar relationship between metabolism and duration (Appendix Fig. A.10, A.11).

3.1.3. Regional and industrial distribution of Changers and Holders

Table 4 shows the number of companies with their duration, metabolism, and the number of business partners for Changers and Holders, respectively. There were 205 Changers and 205 Holders with an average metabolism of 0.413 for Changers and 0.005 for Holders. Changers tended to have more business partners than Holders.

We found a typical difference in the location of Changers and Holders among the six prefectures in the Tohoku region (Fig. 5). The dots represent the location of Changers and Holders, and the colour of the dots represents their metabolism values. By definition,

Table 4
Average values of Changers and Holders.

Type	Firms	Duration	Metabolism	Transactions
Changer	205	10	0.413	14.780
Holder	205	10	0.005	12.951

Table 5
Number of Changers and Holders by industry and prefecture.

Industry/Prefecture	Metabolism	Firms	Changers	Holders
Construction	0.189	6565	**159**	36
Manufacturing	0.117	3076	10	57
Service	0.121	654	7	16
Transportation	0.142	832	5	2
Wholesale–Retail	0.107	4070	16	**75**
Akita	0.130	1682	21	22
Aomori	0.150	1899	14	26
Fukushima	0.153	3618	47	32
Iwate	0.115	2186	6	**51**
Miyagi	0.169	4090	**101**	43
Yamagata	0.132	2847	13	31

Table 6
Scores.

	Data1	Data2	Data3	Data4	Data5
F1 score	0.852	0.827	0.848	0.844	0.834
Precision	0.801	0.793	0.803	0.802	0.795
Recall	0.910	0.865	0.897	0.890	0.877

Changers tended to be closer to red and Holders closer to blue. The distribution shows that Changers tended to cluster in Miyagi Prefecture, while Holders tended to cluster in Iwate Prefecture.

Table 5 shows the average level of metabolism, average duration, number of firms, and number of Changers and Holders for firms with ten or more average clients in five major industries and prefectures in the Tohoku region. We found trends that the construction industry and Miyagi Prefecture tended to have more Changers, while the wholesale and retail industry and Iwate Prefecture tended to have more Holders.

3.2. Effect of changing business partners

3.2.1. Accuracy of modelling fixed business relationships

The performance of predicting fixed customer-supplier relationships is shown with precision, recall, and F1-score in Table 6. On average, the F1 score for predicting customer-supplier fixation was about 0.841, and the scores did not vary much between the datasets.

3.2.2. Features affecting the fixation of business relationships

We examined our learning model in detail to identify the features that were important for our prediction. The weights of the features for predicting committed customer-supplier relationships are shown in Table 7. Overall, duration showed the strongest contribution to the prediction of fixed customer-supplier relationships. It indicates that enterprises with fixed transactions had a shorter duration than enterprises that changed partners. The number of transactions also had a significant impact, i.e. firms with many business partners were more likely to change their partners. In addition, industry had a significant impact on each dataset, suggesting that the range of fixed relationships differs between industries. Sales had a negative impact, although the amount varied between the datasets. In order to compare the performance of the models and to investigate statistical validation, we applied the statistical analysis of logistic regression reported in the Appendix A.10, with statistics of coefficients, p-values, standard errors and pseudo R-squared, which showed similar trends in the importance of the features.

3.2.3. Multiple comparison test of groups of firms by quantile of metabolism

To confirm the significant difference in the average duration of the nine groups of companies divided by the metabolism quantile (3), we applied the Tukey-Kramer method, a typical multiple comparison test. Fig. 6 shows the distribution of duration for each group of companies. The ascending order of the alphabets at the top of the figure corresponds to the ascending order of the group means. If there is no significant difference between the group means, the same alphabet is assigned. The relationship between metabolism and duration was not monotonically positive, but rather an inverted U, with low duration for very low and high metabolism and

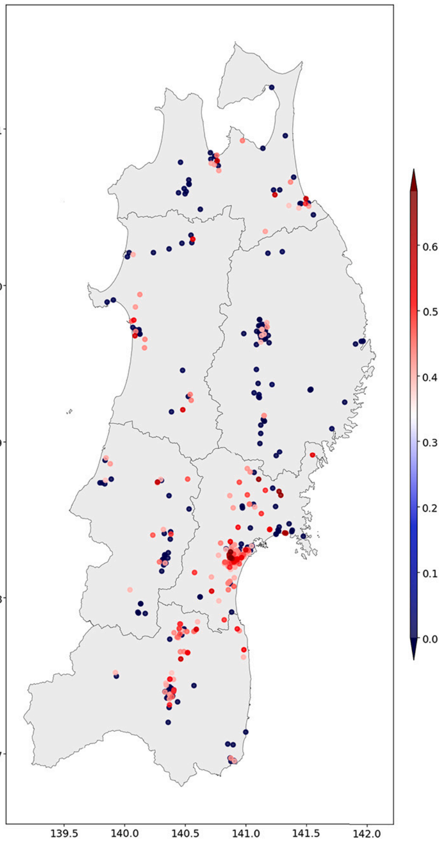

Fig. 5. Locations of Changers and Holders. Red dots represent the locations of Changers and blue dots represent those of Holders. The six prefectures in the Tohoku region are located as follows. Top: Aomori, top left: Akita, top right: Iwate, bottom left: Yamagata, bottom right: Miyagi, bottom: Fukushima.

Table 7
Estimate effect of changing business partners.

Features	Data1	Data2	Data3	Data4	Data5
Sales	-1.164	-0.566	-0.214	-0.438	-0.543
Age	-0.236	-0.096	0.006	-0.072	0.033
Region	0.019	0.132	0.053	0.039	-0.018
Sales growth	0.088	0.154	0.147	-0.005	0.081
Industry	0.407	0.313	0.373	0.437	0.470
Plants	0.621	0.537	0.356	0.079	0.501
Transactions	0.653	0.751	0.564	0.480	0.607
Employees	0.850	0.736	0.048	0.431	0.755
Duration	**1.900**	**2.017**	**1.654**	**1.871**	**1.776**

high duration for companies in the middle of the metabolism distribution. Among the nine groups of firms, the group with the lowest metabolism (quantile 2.5) has the shortest survival, followed by the group with the highest metabolism (quantile 97.5) and the group with quantile 95. Most of the enterprises in quantile 2.5 had a metabolism of 0, i.e. they did not change their business partners at all, while the enterprises in quantile 97.5 had an average metabolism of 0.456, i.e. about half of the enterprises changed their business partners. Firms with the longest duration were observed in both quantile 25 and quantile 50, with no significant difference between the two groups. The statistics for all combinations of firms divided by the nine quantiles are shown in the annexed Table A.11.

Fig. 7 shows a plot of the 95% confidence interval of the significant difference between the groups for the mean duration. As this is a 9-group multiple comparison test, the differences estimated for the two groups of 36 combinations are indicated by •, and the lower and upper limits of the 95% confidence interval are (-). The vertical dashed line indicates that the difference in means is zero. A 95% confidence interval that does not cross the dotted line means that the difference is significant at the 5% significance level. For example, the group of companies with quantile 50 has a higher average duration of 4.5 years than the group of companies with quantile 2.5, and the confidence interval is narrower and does not cross 0, meaning that the average duration is statistically significantly longer.

As an overall trend, the group of enterprises in quantile 2.5 was significantly different from the group of enterprises in all other quantiles, with a shorter average duration. On the other hand, a comparison with quantiles 25 and 50, which have the largest

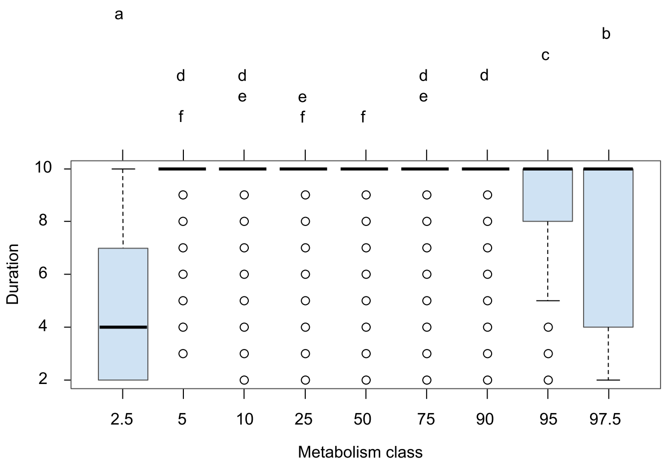

Fig. 6. Results of Multiple Comparison Tests of quantile of Metabolism and Duration. The alphabets represent the significant difference of the duration among the nine groups classified by the values of metabolism.

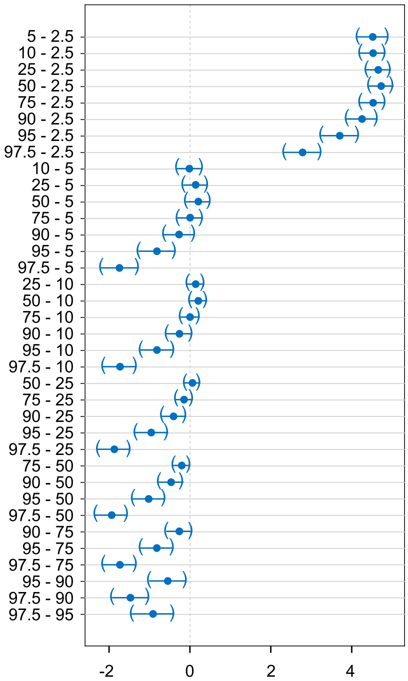

Fig. 7. 95% confidence interval for the duration at the quantile level of metabolism. Significant differences of 36 pairs of 9 groups are represented with the lower and upper limits of the 95% confidence interval. The vertical dotted line indicates no significant differences.

significant difference compared to quantile 2.5 and the longest average duration, showed that the significant difference with quantiles 25 and 50 increased as the average metabolism increased from quantile 90, 95 to 97.5. The average metabolism of the group of firms in quantile 90 was 0.273, and the groups in quantiles 95 and 97.5 had an even higher average metabolism, suggesting that firms that replace about 27% or more of their business partners tend to have shorter life spans as their metabolism increases.

4. Discussion

Understanding supply chain trends and disruption risks has become increasingly important in today's volatile marketplace. This is due to unexpected natural disasters, financial crises, pandemics and increased global awareness of corporate social responsibility. In order to adapt to rapidly changing market conditions, it is important for companies to integrate and flexibly restructure both internal and external corporate capabilities and resources. In this study, we quantitatively investigated how firms' ability to adapt to the turbulent market depends not only on the stable maintenance, but also on the flexible recombination of inter-firm relationships.

The proposed index of metabolism could be used to study the micro-level dynamics of interconnected firms and the ability of these firms to respond to market changes or plan strategies to mitigate the risk of supply chain disruptions.

Based on the results of our study, we found an inverted U-shaped relationship between metabolism and duration when taking duration on the vertical axis and metabolism on the horizontal axis. The modelling result of fixed transactions shown in Table 7 and the multi-comparison test of varied metabolism shown in Fig. 6 and 7 suggest that excessive immobilization of business relationships can lead to a loss of business competitiveness. The 10-year survival rates of firms with low metabolism and fixed transactions were particularly low, suggesting that they were unable to adapt to the rapidly changing business environment, including the Lehman shock and the Great East Japan Earthquake. Statistical analysis of the level of metabolism and the duration of existence of firms showed that firms with a long duration of existence had an intermediate level of metabolism, neither too low nor too high. Firms with fixed transactions (low metabolism) tended to disappear from the market. Firms with extremely volatile transactions (high metabolism) also tended to have shorter survival periods. In short, both types of firms that rarely or drastically changed their trading partners were at a disadvantage in the competition for survival on the market. Many theoretical models and empirical studies have shown that there is an appropriate value in the medium where both poles are abolished. However, to the best of our knowledge, this is the first analysis that clarifies the correlation between the metabolism and duration of firms based on the dynamics of their transactions.

4.1. Two antagonistic forces for evolution

Successful innovation networks have been known to balance two antagonistic forces [55,35,18]. Flexible network structure and high absorptive capacity for new entrants and new information are considered important for innovation. A network with fixed inter-firm relationships and unchanging cluster boundaries is unlikely to generate innovation. On the other hand, if the network structure is too unstable, it is difficult for firms to develop new competencies because it is difficult to build trust between firms and therefore important ideas for technological innovation are not shared. Given that living organisms have evolved through rare genetic replication errors, the inter-firm network could also evolve through rare replacement of its transactions. Evolution is a dual mechanism that intertwines the forces that seek to enforce universality with the forces that seek to change it [56]. It is therefore important to consider two antagonistic forces at the micro level when analysing a dynamic and evolving model of economic growth. In terms of the degree of metabolism in this paper, it can be said that there are two forces at work at the firm level: the force to maintain existing business partners and the force to change business partners. The fact that metabolism was around 10% for long-established firms indicates that the forces to maintain transactions are stronger than the forces to change them, and the balance between the two forces is tilted in favour of maintenance. It implies that the paradoxical balance of what does not change changing is a driving force of evolution, not only in the biological world but also in the economic system of inter-firm networks.

4.2. Daily operations to prepare for exogenous shocks

Resilient supply chains must be designed to withstand and recover from disruptions quickly and at minimal cost [44]. However, in practice, crisis resilience is not achieved instantly; it requires the accumulation of daily supply chain operations for survival that flexibly adapt to changing environments [57]. According to our previous study, a similar correlation between metabolism and duration was also observed in the Chubu and Kyushu regions, which are far from the disaster-stricken Tohoku region [58]. Therefore, the metabolism of business transactions is not a unique phenomenon in crisis response. Instead, it may be a fundamental survival mechanism in the activities of healthy companies that adapt to changing environments.

Opportunities for innovation often arise from exposure to different technologies and sources of knowledge, which should be facilitated by movement and exchange between regional clusters and openness to heterogeneous information from distant sources [59]. The finding that the wholesale-retail industry had a low metabolism with many Holders was consistent with the reality of the industry in Japan, with little change in business transactions, low productivity and lagging innovation [60]. Construction, however, had high metabolism, with many Changers, resulting in the highest recovery rate in sales and employee numbers compared to pre-disaster levels. According to the Tohoku Bureau of Economy, Trade and Industry's reports on the three affected prefectures, Miyagi Prefecture experienced the largest decline in shipments after the earthquake, followed by the highest recovery and growth. Iwate did not decline as much as Miyagi and grew beyond recovery. Fukushima recovered, but at a level below the national average. The finding that Miyagi Prefecture had many Changers suggests their roles in its high economic vitality to mitigate the disruption of the disaster and drive the growth of the regional economy. Supply chain flexibility with an appropriate rate of metabolism is necessary both to ensure innovation capacity and to maintain resilience to prepare for the crisis.

4.3. Indicator of regional industrial dynamism

Unexpected supply chain disruptions have been common in recent years due to major economic shocks caused by natural or man-made disasters such as the bursting of the IT bubble, the Lehman shock, the Great East Japan Earthquake, COVID-19 and the war in Ukraine. The volatile and rapidly changing market environment of recent years suggests that it is increasingly important to measure firms' ability to adapt to their environment. However, it is difficult to adequately capture the picture of the industrial ecosystem, which strongly influences the activities and growth of enterprises, with conventionally used static regional indicators such as GDP, value of shipments, number of establishments and industry specialisation coefficients. The business ecosystem in a region is constantly changing and it is difficult to capture its dynamics without a data-based approach. There is a need for new dynamic quantitative indicators that are different from static regional and industry economic indicators. The results of this paper's objective analysis of the metabolism of inter-firm networks can provide useful information for understanding the dynamic structure of regional industries and the innovation capacity of firms in regions. The metabolism captures the dynamics of business transactions and can be used as a new macroeconomic indicator of regional economic trends.

5. Conclusions

In this paper, we present measures of the dynamics of inter-firm transactions using a quantitative index of firm metabolism, which has been recognised in theoretical research and case studies as playing an essential role in innovation. Using large-scale data on business transactions in the Northeast over a 10-year period from 2007 to 2016, we found that most firms changed their business partners by 10–20% each year. We found that both firms with low metabolism or fixed transactions and firms with extremely high metabolism tended to survive for a short time and then exit the market. Comparisons by industry and region suggest that the demand for large-scale reconstruction has affected the metabolism of firms. Many large construction firms with high metabolism were located in hard-hit regions, such as Miyagi and Fukushima prefectures. Using data on business transactions in the Tohoku region, we confirmed a statistically significant difference between the degree of metabolism and the duration of firms. The results of this study's objective analysis of the metabolism of business transactions suggest that supply chain fluctuations can be captured from a micro perspective, and that the ability to adapt to environmental changes is reflected in a firm's degree of metabolism.

There are several caveats to our analysis. First, the transaction data used in this paper were collected for up to 40 main trading partners each and do not cover all trading partners of each company. Although the data were updated annually, the companies that were considered important partners by each company in a given year were listed and not otherwise included in the data. Therefore, there is a discrepancy in the firms' perception of the importance of partners, i.e. important partners for a firm are not equally important for the partner. In particular, firms in Tokyo did not always list firms in Tohoku as their most important partners, whereas most firms in Tohoku considered their partners in Tokyo to be important. While in this study we defined metabolism as the extent to which a firm replaced its partners based on changes in the firm's recognition, another possible definition of metabolism is to measure the extent to which a firm was listed as a partner by other firms based on the ratings of several firms. Although we confirmed that the correlation between metabolism and duration also applies to this multiple valuation of metabolism, we did not include it as it is beyond the scope of this paper. Second, we used the inter-firm network as unweighted and undirected in this study. The possible extension is weighted and directed network by including money flow and distinguish suppliers and customers, which is for future study. Third, in order to obtain valid calculation results of the metabolism, the companies analysed in this paper were limited to those with ten or more average transactions. Companies with a smaller number of customers were excluded from the analysis. Fourthly, the proposed index, metabolism, was defined as the average value of the partner replacement rate for each company over the period, and thus cannot handle time-series fluctuations. In addition, the level of metabolism increases in all cases of increase, replacement or decrease in the number of client firms (Fig. 2), making it impossible to distinguish between these three factors when interpreting changes in the level of metabolism. Finally, although we found a statistically significant difference between level of metabolism and duration, this does not prove causality between them. These points are left for future research.

CRediT authorship contribution statement

H.Y. designed research; H.Y. conducted the experiments and analysed data; H.Y. wrote the manuscript; H.Y. and I.S. discussed the results and reviewed the manuscript; I.S. supervised the project.

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.

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Appendix A. Supplementary

A.1. Transaction similarity by the number of business partners

We investigated the relation between the number of business partners and the average transaction similarity calculated by Jaccard index of business partners in each two consecutive years from 2007 to 2016. Fig. A.8 shows the average similarity of partner similarities of nine terms of the two consecutive years in Fig. A.9. In every figure, the similarity decreases as the number of business partners increase until reaching 10 partners.

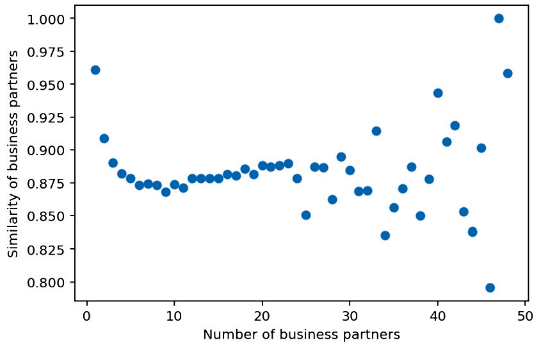

Fig. A.8. Average transaction similarity by the number of business partners in ten years.

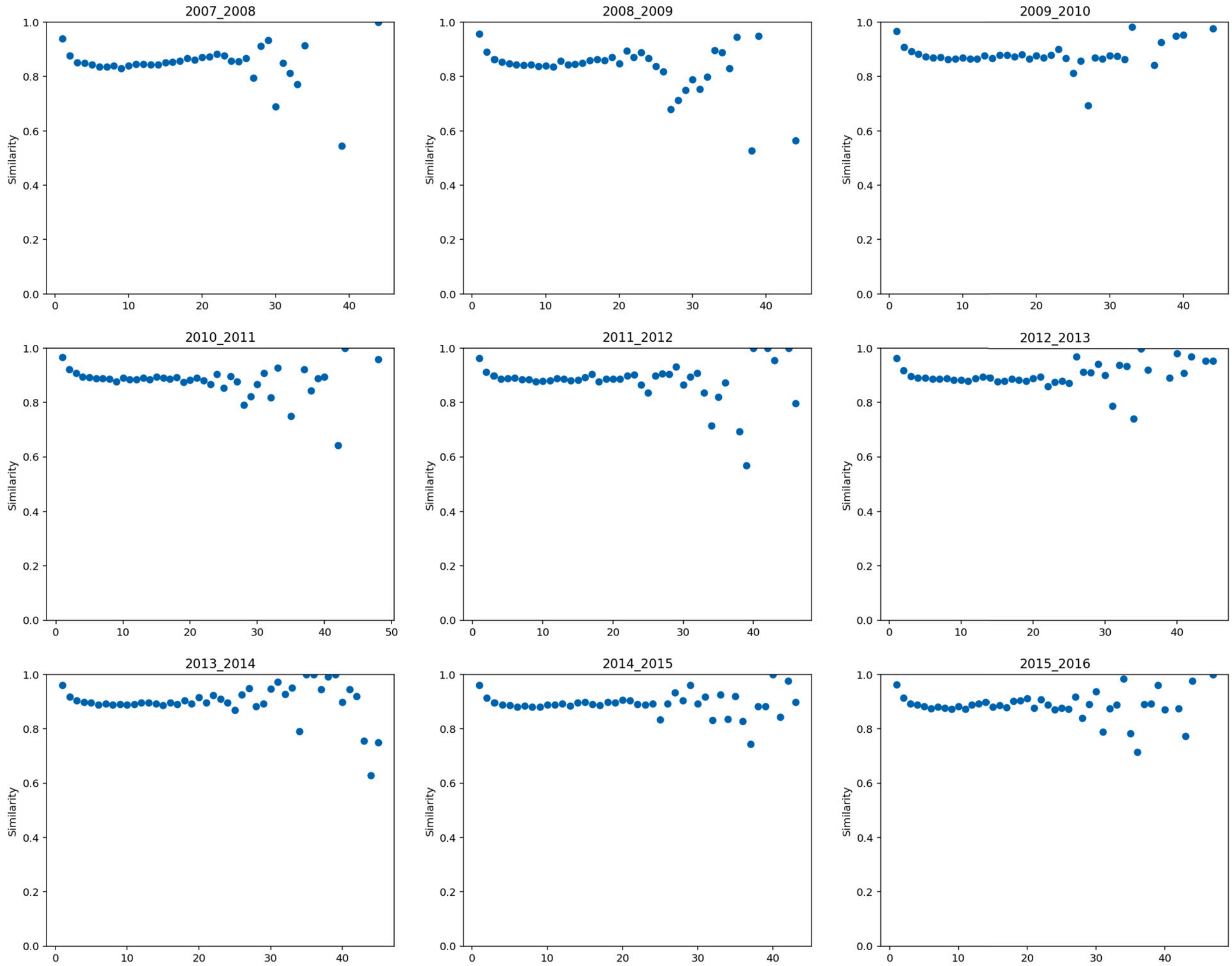

Fig. A.9. Average transaction similarity by the number of business partners in each two consecutive years from 2007 to 2016.

A.2. Metabolism and duration

Fig. A.10, A.11 shows the number of firms divided by 15 different ranges of metabolism by each duration. Since the majority of firms had 10-year duration, the plotted range was divided into two, with and without 10-year duration included. The orange and yellow bars with 10 and 9-year duration, respectively, showed the mode of metabolism around 0.1, while the mode of metabolism tended to decrease as the duration decreases for companies with eight years or less of duration. The results suggest that there was a certain level of metabolism for companies to survive for a long period of time, and that if the level of metabolism was too low,

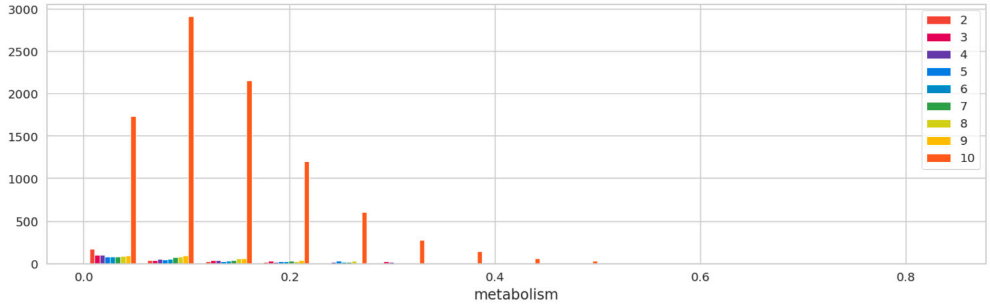

Fig. A.10. Number of firms by metabolism and Duration 1.

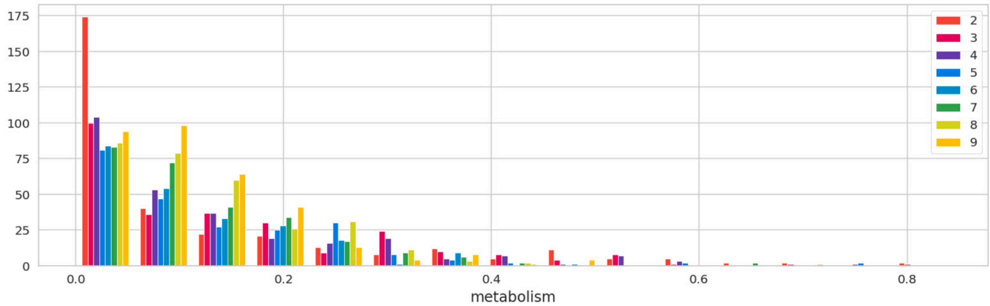

Fig. A.11. Number of firms by metabolism and Duration 2.

Table A.8
Number of firms by duration.

Duration	2	3	4	5	6	7	8	9	10
Firms	322	269	272	228	228	266	299	327	9131

Table A.9
VIFs of features.

Features	Data1	Data2	Data3	Data4	Data5
Sales	6.340	2.065	4.048	3.126	1.627
Age	1.128	1.130	1.131	1.145	1.115
Region	1.020	1.029	1.031	1.027	1.017
Sales growth	1.061	1.052	1.052	1.054	1.055
Industry	1.059	1.056	1.046	1.061	1.040
Plants	2.273	1.482	1.559	1.204	1.156
Transactions	1.057	1.028	1.049	1.044	1.047
Employees	4.578	1.797	3.614	3.484	1.814
Duration	1.085	1.078	1.090	1.070	1.063

companies tended not to survive for a long time. The number of firms were similar in scale except for firms with 10-year duration (Table A.8).

A.3. Testing for multicollinearity

The Variance Inflation Factors (VIF) is a measure of how much the variance of the estimated regression coefficients is increased due to multicollinearity. By using the coefficient of determination in a multiple regression analysis with one explanatory variable as the objective variable and with other explanatory variables, VIF is defined as follows,

$$VIF = \frac{1}{1 - R^2} \tag{A.1}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - f_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y}_i)^2} \tag{A.2}$$

Table A.10
Logistic regression of Metabolism class with Stepwise model selection.

	Model1	Model2	Model3	Model4	Model5	Model6	Model7	Model8	Model9
Region	0.049								
	(0.093)								
Sales growth	0.122	0.124							
	(0.091)	(0.090)							
Age	−0.141	−0.143	−0.164*						
	(0.098)	(0.098)	(0.096)						
Plants	0.269	0.265	0.258	0.244					
	(0.184)	(0.185)	(0.185)	0.182					
Employees	0.426	0.425	0.463	0.415	0.593**				
	(0.309)	(0.309)	(0.318)	(0.319)	(0.284)				
Sales	−0.442**	−0.443**	−0.459**	−0.436**	−0.503***	−0.142			
	(0.212)	(0.211)	(0.212)	(0.216)	(0.192)	(0.095)			
Industry	0.357***	0.353***	0.357***	0.340***	0.314***	0.305***	0.309***		
	(0.093)	(0.093)	(0.093)	(0.092)	(0.089)	(0.089)	(0.089)		
Transactions	0.694***	0.699***	0.706***	0.692***	0.700***	0.689***	0.672***	0.704***	
	(0.111)	(0.110)	(0.110)	(0.109)	(0.109)	(0.109)	(0.108)	(0.109)	
Duration	2.006***	2.001***	1.998***	1.954***	1.964***	1.968***	1.953***	1.977***	1.880***
	(0.127)	(0.126)	(0.126)	(0.121)	(0.122)	(0.121)	(0.120)	(0.121)	(0.113)
Adj. R-squared:	0.426	0.426	0.424	0.422	0.421	0.417	0.415	0.406	0.370

Note: Regression coefficients reported using Data3 with 502 negative and sampled positive instances of the same size. Standard errors are listed in parentheses. We report the results of a logit model with Metabolism class as a binary outcome. Metabolism class is a binary variable equal to 1 if the firm changes at least one business partner during the setting period of 10 years and 0 otherwise. We used model selection techniques of stepwise regression based on the significance of explanatory variables. * $p < .10$, ** $p < .05$, *** $p < .01$.

Table A.11
Multiple comparison tests at the quantile point level of metabolism.

Null hypothesis	Estimate Std.	Error	t value	Pr(>|t|)
5 - 2.5 = 0	4.528	0.117	38.781	< 0.001 ***
10 - 2.5 = 0	4.520	0.095	47.511	< 0.001 ***
25 - 2.5 = 0	4.663	0.090	51.656	< 0.001 ***
50 - 2.5 = 0	4.727	0.090	52.364	< 0.001 ***
75 - 2.5 = 0	4.524	0.095	47.543	< 0.001 ***
90 - 2.5 = 0	4.257	0.117	36.514	< 0.001 ***
95 - 2.5 = 0	3.708	0.143	25.981	< 0.001 ***
97.5 - 2.5 = 0	2.788	0.143	19.513	< 0.001 ***
10 - 5 = 0	-0.008	0.095	-0.079	1.000
25 - 5 = 0	0.135	0.091	1.491	0.841
50 - 5 = 0	0.199	0.091	2.196	0.376
75 - 5 = 0	-0.004	0.095	-0.043	1.000
90 - 5 = 0	-0.271	0.117	-2.319	0.300
95 - 5 = 0	-0.820	0.143	-5.738	< 0.001 ***
97.5 - 5 = 0	-1.739	0.143	-12.156	< 0.001 ***
25 - 10 = 0	0.143	0.060	2.369	0.273
50 - 10 = 0	0.206	0.060	3.430	0.015 *
75 - 10 = 0	0.003	0.067	0.051	1.000
90 - 10 = 0	-0.263	0.095	-2.766	0.110
95 - 10 = 0	-0.812	0.126	-6.455	< 0.001 ***
97.5 - 10 = 0	-1.732	0.126	-13.736	< 0.001 ***
50 - 25 = 0	0.064	0.052	1.224	0.943
75 - 25 = 0	-0.139	0.060	-2.311	0.305
90 - 25 = 0	-0.406	0.090	-4.493	< 0.001 ***
95 - 25 = 0	-0.955	0.122	-7.814	< 0.001 ***
97.5 - 25 = 0	-1.874	0.122	-15.309	< 0.001 ***
75 - 50 = 0	-0.203	0.060	-3.371	0.018 *
90 - 50 = 0	-0.470	0.090	-5.200	< 0.001 ***
95 - 50 = 0	-1.019	0.122	-8.336	< 0.001 ***
97.5 - 50 = 0	-1.938	0.122	-15.830	< 0.001 ***
90 - 75 = 0	-0.267	0.095	-2.802	0.100
95 - 75 = 0	-0.816	0.126	-6.482	< 0.001 ***
97.5 - 75 = 0	-1.735	0.126	-13.763	< 0.001 ***
95 - 90 = 0	-0.549	0.143	-3.846	0.003 **
97.5 - 90 = 0	-1.468	0.143	-10.273	< 0.001 ***
97.5 - 95 = 0	-0.919	0.165	-5.574	< 0.001 ***
Signif. codes	0‘***’	0.001‘**’	0.01‘*’	0.05‘.’

where R^2 is the coefficient of determination representing the goodness of fit of the model, $y = \{y_1, y_2, \cdots, y_N\}$ is the observed value, and $f = \{f_1, f_2, \cdots, f_N\}$ is the estimated value by the regression equation.

VIFs greater than 5 or 10 suggest critical levels of multicollinearity where the coefficients are poorly estimated, and the p-values are questionable. Investigating the correlations of features by VIFs, we confirmed that their relationships were not severe enough to warrant corrective measures, and therefore, all the features were applied to the analysis.

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