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ORIGINAL PAPER

# Identification of changes in the economic interactions among sectors from 1995 to 2010 for Chicago economy using hierarchical feedback loop analysis

**Xiuli Liu**[1,2,3] · **Geoffrey J. D. Hewings**[4]

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## Abstract

In this paper, hierarchical feedback loop analysis is employed to identify changes in the economic interactions among sectors during the process of structural transformation of the Chicago economy. The application in our paper differs from previous studies adopting this methodology as it focuses on the time dimension of change through analysis of feedback loops every 5 years from 1995 to 2010. A total of 36 hierarchical feedback loops for years 1995, 2000, 2005 and 2010 were obtained. The first two feedback loops captured the main character of the economic structure transformation. The linkages strength between five pairs of sectors which include linkages from hotels, personal and business services to construction, from finance and insurance to wholesale and retail trade, etc., accounted for 83.5% of the intensity change in the first feedback loop from 1995 to 2010. Structural change of linkages played little role in the complexity change of the second feedback loop. The change of linkages strength from wholesale and retail trade to construction, from rubber and miscellaneous plastics products to chemicals and allied products accounted for about 83.0% of this latter loop. The economic transformation of Chicago economy showed that the development of services has not come at the expense of the decline of industry. Over the period in question, the Chicago economy became more diversified.

**JEL Classification** C67 · D57

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✉ Xiuli Liu
xiuli.liu@amss.ac.cn

Extended author information available on the last page of the article

## 1 Introduction

Economic systems are increasingly built on interdependencies; the processes of estimating, interpreting and accounting for changes in these interdependencies have generated a number of different techniques and approaches. The recent profusion of studies directed at trade in value added (see, for example, Steen-Olsen et al. 2016) illustrates some of the important changes that have characterized the changing geography of trade linkages at the global level. The present paper explores the structural transformation of a single economy (the Chicago metropolitan region) with a particular focus on the changing interaction between sectors, a perspective that has once again become a major topic for economic analysis (Berthold et al. 2013; Liu et al. 2016). Earlier work (Hewings et al. 1998; Romero et al. 2009) had explored the nature and strength of changes in the degree of intermediation within the Chicago region and found that while the region as a whole was hollowing out (a decline in the degree of intermediation in production), a small set of interactions was increasing in intensity as a result of a process of functional fragmentation. What is needed, therefore, is an approach that stresses the systemic complexity of economic structure and one that can also be used to revise and extend established paradigms in economic theory (Schweitzer et al. 2009). Thompson (1965) considered that the evolution of the economy's structure transformation is logistic, with a slow accumulation of interaction effects characterizing the early period before a takeoff into an accelerated period of growth. As the economy reaches maturity, the deepening of the interactions slows down. It is here that for the most part, the empirical evidence ends. Jensen et al. (1986, 1988), in a series of papers, explored the ways in which development would be accompanied by an essential deepening of the intensity of interaction between sectors and proposed the development of a taxonomy of economies based on their economic structure as manifested in the structure of the input–output connectivity. However, their analysis and progress in this area have been hampered by a dearth of data, especially a time series of input–output tables.

The metropolitan economy of Chicago has experienced a significant transformation in its economic structure over the past 30 years. It represents an exemplar of an older economy whose domination by manufacturing has been replaced by a much more diversified economy. Israilevich and Mahidhara (1991) noted that there had been an important exchange; at a seven-sector aggregated level, firms were becoming less dependent on sources of manufactured inputs produced in Chicago and more dependent on services that were being produced in the metropolitan region over the period 1970–1990. Schindler et al. (1995) also found that during 1970s and 1980s, Chicago's economic structure changed dramatically with services coming to dominate both output and employment. It is possible to argue that the case of the Chicago economy presents one stage of a series underlying the processes of complexity development in a metropolitan region (see Sonis et al. 1997 for fuller explanation). To produce an economic photograph of the changes in the Chicago region, annually, for the period 1975–2011, Sonis and Hewings (1998) explored the nature of these structural changes; the resulting picture, at the nine-sector level of detail, revealed a hollowing-out process.

Drawing on the limited empirical and theoretical contributions that are available, these studies employed aggregated industrial sectors (seven or nine sectors, respectively), and thus, they provided only an aggregate view of structural change; what these movements in composition do not reveal is whether there have been any underlying changes in the internal-to-the-region exchange among sectors. The processes of structural change had become more complicated, requiring alternative, complementary tools to be applied to provide a more complete picture of the changes (Romero et al. 2009). In the present paper, hierarchical feedback loop analysis developed by Sonis and Hewings (1988, 1991) is employed. The innovation is to explore the use of this methodology to trace and interpret structural changes in a single regional economy over time (1995–2010). The methodology can be viewed as a complement to other approaches to the measurement of structural change with the distinguishing feature that it highlights subsystems of linkages that are extracted in a hierarchical fashion. By examining the intensity of change within each feedback loop, the methodology can help to identify some of the changes caused by spatial and functional fragmentation of production (see Romero et al. 2009) with the former likely to see a decrease and the latter an increase in intermediation. By enhancing the analytical toolbox, a more complete overview of the process of economic development, manifested through changes in economic structure, can be presented.

The reminder of this paper is organized as follows. Section 2 introduces the basic elements of the hierarchical feedback loop approach. Section 3 briefly describes the derivation of Chicago input–output tables using the Chicago region econometric input–output model (CREIM). Section 4 presents the feedback loops of the Chicago economy over the period of 1995–2010 and with some interpretive analysis. The fifth section concludes with some summary remarks.

## 2 Hierarchical feedback loop analysis

A series of transactions, in which each sector appears only once with one incoming flow and one outgoing flow, may indeed be called a feedback loop,[1] because each sector in such a loop affects itself at the end of the loop (assuming one starts the loop with the sector in question).[2] A feedback loop is complete if it includes all the sectors. The economic interpretation of a feedback loop is straightforward; it indicates how strongly (at each hierarchical level) each sector is tied to all other sectors included in that loop. It provides a more complete picture of the structure of flows and offers additional information by presenting the paths of interaction among sectors. As such, it complements rather than replaces more traditional multiplier-based interpretations of the importance of each sector (Sonis et al. 2002). In the analysis to be performed, attention will be directed to complete loops and their subloops. By

[1] This section draws on Sonis et al. (1995).

[2] In other papers, Sonis et al. (2002) described feedback loops as spatial production cycles since they highlight the circularity in production systems.

focusing on these loops, one can evaluate the place and position of each sector relative to all other sectors in Chicago.

Considering only complete feedback loops is technically possible, as each non-complete feedback loop can be extended to become a complete loop through the addition of loops including the sectors outside the non-complete loop. Moreover, a hierarchical analysis of the set of all complete loops is simpler than a hierarchical analysis of the set of all possible loops. For a set of $n$ sectors, the number of complete feedback loops is already equal to $n!$.

A complete feedback loop is either closed or can be decomposed into a set of closed subloops. If the entering flow and the leaving flow for the same sector are identical, we have the smallest closed subloop possible, i.e., the effect that a sector exerts directly on itself—the self-effect. It is important to note that the matrix form of a complete feedback loop can be represented with the help of a sub-matrix $Tx$ of flows extracted from the matrix $T = \left| t_{ij} \right|$ of all the aggregated transaction flows. Such a sub-matrix $Tx$ represents a complete feedback loop if it includes in each row and in each column only one nonzero entry from the matrix $T$ and contains zeros elsewhere. One can define the 'flow intensity' $Vx$ of a complete feedback loop as the sum of all the transaction flows of the corresponding sub-matrix $Tx$.

If all the nonzero entries of $Tx$ are replaced by 1's (thus converting the matrix into a Boolean form); the result is the so-called permutation matrix $Px$. This Boolean matrix corresponds to some permutation of the sequence of numbers 1, 2… $n$. Such a permutation (of sectors) represents the structure of the corresponding complete feedback loops. The sub-matrices $Tx$ are referred to as 'quasi-permutation matrices'.

The hierarchy of all complete feedback loops is defined as the sequence of quasi-permutation sub-matrices $Tx$, chosen according to the rank size of their flow intensities. This means that on the top of the hierarchy, one finds the complete feedback loop with the maximal flow intensity. This top-down decomposition may be considered analogously to an exfoliation process in the removal of the layers of the onion. The feedback loops on the inner hierarchical level of economic activities should be placed into the loops of the higher levels in the form of the matryoshka doll. The superposition principle considers the economic system as a decentralized system that is comprised of a set of subsystems acting according to different and often conflicting and non-commensurable objectives. These objectives may be presented in the form of extreme tendencies or trends; the hierarchical viewpoint enables the analyst to extract the tendencies from the most to the least importance. In this fashion, the procedure is not unlike that used in principal component analysis (Sonis et al. 2001).

The problem of the determination of the quasi-permutation sub-matrix with the maximal flow intensity is mathematically equivalent to the solution of the optimal personnel assignment of $n$ persons (here rows) between $n$ jobs (here columns), in such a way that one person will have one job, while profit is maximized (see Dantzig 1963). Here, 'profit' is defined by the size of the transaction flows in matrix $T$. Further details of the procedure can be found in Sonis and Hewings (1988, 1991). In this paper, a MATLAB program was compiled to find the quasi-permutation sub-matrices $Tx$.

Hierarchical feedback loop analysis extended the analytical procedure introduced earlier by Pyatt and Round (1979) (see also Round 1979, 1985, 1988), who developed a method for the decomposition of multipliers in a social accounting matrix for a single economy. It offers a method of placing feedback effects on a network and provides the potential for uncovering the nature, strength and spatial linkages of intermediate flows (Sonis and Hewings 1988). It is also important to stress that the hierarchical feedback loop approach can be applied to more extensive accounting systems; while the attention in this paper is focused on the intermediate transactions within Chicago, there is no reason why attention could not be directed to a set of interregional social accounts that include the flows of labor and capital.

## 3 Data

The data were derived from a time series (1995–2010) of input–output tables, featuring 36 sectors (see Table 1) that were derived from the Chicago region econometric input–output model (CREIM). CREIM offers a methodological innovation, initially proposed by Richard and Conway (1990) and Conway and Richard (1991), whereby a quasi-general equilibrium adjustment process is adopted in which changes in the input coefficients assume a major role in clearing markets. The additional innovation was the ability to extract the annual (modified) input–output tables from the model (Israilevich et al. 1997 for details of the extraction methodology). The model is a system of linear and nonlinear equations formulated to predict the behavior of 151 endogenous variables and consists of 123 behavioral equations, 28 accounting identities and 68 exogenous variables. CREIM identifies 36 industries and three government sectors. The model is updated annually and recalibrated every 5 years; in the last 5 years, attention has been directed to greater disaggregation of household demand and the concomitant disaggregation of payments of wages and salaries (Kim and Hewings 2013, 2019; Kim et al. 2015; Hewings et al. 2017).

## 4 Application

As Carter (1970) noted, structural change is a moving average process that often reveals noticeable changes over longer time spans. Although input–output tables were obtained for each year for the period 1995 to 2010, the hierarchical feedback loops were only extracted and evaluated for the years 1995, 2000, 2005 and 2010 for purposes of illustration. The values of $Vx$ and its proportion to the total intermediate flow are presented in Table 2.

### 4.1 The proportions analysis of each feedback loop

Table 2 and Fig. 1 reveal that the proportion of each feedback loop ($Vx$) to the total intermediate flow was stable from 1995 to 2010. The first feedback loop accounted

**Table 1** Sector definitions

| Sector description | 36-Sector number | 9-Sector number | SIC codes |
|---|---|---|---|
| Livestock and other agricultural products | 1 | 1 | 01, 02 |
| Forestry and fishery, agricultural services | 2 | 1 | 07–09 |
| Mining | 3 | 1 | 10–14 |
| Construction | 4 | 2 | 15–17 |
| Food and kindred products | 5 | 3 | 20 |
| Tobacco manufactures | 6 | 3 | 21 |
| Textiles and apparel | 7 | 3 | 22, 23 |
| Lumber and wood products | 8 | 4 | 24 |
| Furniture and fixtures | 9 | 4 | 25 |
| Paper and allied products | 10 | 3 | 26 |
| Printing and publishing | 11 | 3 | 27 |
| Chemicals and allied products | 12 | 3 | 28 |
| Petroleum refining and related industries | 13 | 3 | 29 |
| Rubber and miscellaneous plastics products | 14 | 3 | 30 |
| Leather and leather products | 15 | 3 | 31 |
| Stone, clay, glass and concrete products | 16 | 4 | 32 |
| Primary metal industries | 17 | 4 | 33 |
| Fabricated metal products | 18 | 4 | 34 |
| Machinery, except electrical | 19 | 4 | 35 |
| Electrical and electronic machinery | 20 | 4 | 36 |
| Transportation equipment | 21 | 4 | 37 |
| Scientific instruments, photographic and medical goods | 22 | 4 | 38 |
| Miscellaneous manufacturing industries | 23 | 4 | 39 |
| Transportation and warehousing | 24 | 5 | 40–42, 44–47 |
| Communication | 25 | 5 | 48 |
| Electric, gas and sanitary services | 26 | 5 | 49 |
| Wholesale and retail trade | 27 | 6 | 50–57, 59 |
| Finance and insurance | 28 | 7 | 60–64, 67 |
| Real estate and rental | 29 | 7 | 65, 66 |
| Hotels, personal and business services | 30 | 8 | 70–73, 76, 81, 89 |
| Eating and drinking places | 31 | 8 | 58 |
| Automobile repair and services | 32 | 8 | 75 |
| Amusements and recreation services | 33 | 8 | 78, 79 |
| Health, education and nonprofit organizations | 34 | 8 | 80, 82–84, 86 |
| Federal government enterprises | 35 | 9 | |
| State and local government enterprises | 36 | 9 | |

Table 1 is sourced from Israilevich et al. (1997)

for about 14% of the total intermediate flow. The second accounted for about 10.5%, the third 7.7%. From the seventh feedback loop, their proportions were each smaller than 5%. The larger the value of *x* is, the smaller the proportion.

**Table 2** Top five sectors which had the biggest input proportion in V1 and V2 from 1995 to 2010

| | S27 (%) | S30 (%) | S5 (%) | S4 (%) | S34 (%) | S24 (%) | S31 (%) | S12 (%) |
|---|---|---|---|---|---|---|---|---|
| 1995 T1 | 18.60 | 12.90 | 10 | 6.60 | | 9.50 | | |
| 2000 T1 | 18.57 | 14.86 | 10.05 | | | 9.63 | | 6.44 |
| 2005 T1 | 18.17 | 17.22 | 9.94 | 8.47 | | 9.64 | | |
| 2010 T1 | 17.27 | 20.14 | 9.67 | 6.95 | | 9.43 | | |
| 1995 T2 | 16.90 | 19.10 | | 11.40 | 7.10 | | 9.40 | |
| 2000 T2 | 17.86 | 19.55 | | 11.12 | 6.72 | | 9.26 | |
| 2005 T2 | 19.27 | 19.81 | | 7.52 | 6.21 | | 8.99 | |
| 2010 T2 | 20.90 | 19.92 | | 10.54 | | | 8.58 | |

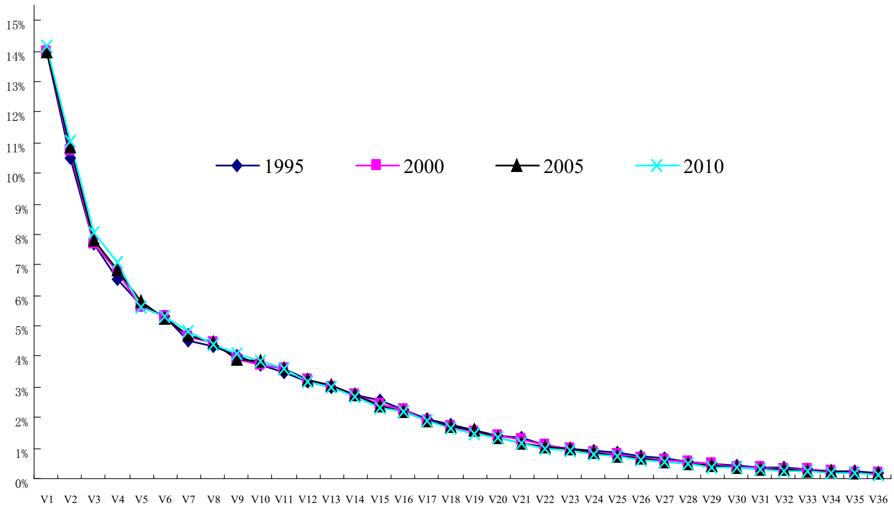


**Fig. 1** Proportion of 36 feedback loops from 1995 to 2010

Table 2 reveals that the flow intensity *Vx* increased steadily from 1995 to 2010. The rate of change of the flow intensity of the first ten feedback loops (*Vx*) during each 5-year period was greater than 10%.

In terms of the sector input proportion of *Vx*, Table 3 shows that sector 30 and sector 27 were ranked first and second in $T_1$ and $T_2$ from 1995 to 2010. The inputs of sectors 30, 27 and 4 were the three main and stable forces of the first two feedback loop intensities. The input proportions of sectors 5, 24, 34, 31 and 12 exhibited more change from 1995 to 2010.

## 4.2 Point change analysis

Table 4 compares the different sectors of matrix *Px* over time intervals of 1 year, 5 years, 10 years and 15 years. Table 4 shows that in one-year time period, from

**Table 3** Different points of the permutation matrix $P_x$ to each feedback loop $T_x$ in different time periods

| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | $P_7$ | $P_8$ | $P_9$ | $P_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *1 year period* | | | | | | | | | | |
| 2002–2003 | 0 | 0 | 0 | 0 | 10 | 14 | 20 | 32 | 36 | 46 |
| *5 years period* | | | | | | | | | | |
| 1995–2000 | 4 | 6 | 14 | 32 | 32 | 40 | 48 | 40 | 42 | 40 |
| 2000–2005 | 12 | 4 | 18 | 36 | 34 | 42 | 48 | 46 | 48 | 48 |
| 2005–2010 | 10 | 18 | 22 | 36 | 40 | 40 | 58 | 44 | 56 | 58 |
| *10 years period* | | | | | | | | | | |
| 1995–2005 | 16 | 10 | 22 | 30 | 44 | 40 | 58 | 48 | 38 | 56 |
| 2000–2010 | 8 | 14 | 26 | 34 | 44 | 44 | 52 | 64 | 70 | 64 |
| *15 years period* | | | | | | | | | | |
| 1995–2010 | 12 | 18 | 30 | 40 | 56 | 52 | 54 | 58 | 64 | 58 |

**Table 4** Different points of the permutation matrix $P_x$ to each feedback loop $T_x$ in different time periods

| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | $P_7$ | $P_8$ | $P_9$ | $P_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *1 year period* | | | | | | | | | | |
| 2002–2003 | 0 | 0 | 0 | 0 | 10 | 14 | 20 | 32 | 36 | 46 |
| *5 years period* | | | | | | | | | | |
| 1995–2000 | 4 | 6 | 14 | 32 | 32 | 40 | 48 | 40 | 42 | 40 |
| 2000–2005 | 12 | 4 | 18 | 36 | 34 | 42 | 48 | 46 | 48 | 48 |
| 2005–2010 | 10 | 18 | 22 | 36 | 40 | 40 | 58 | 44 | 56 | 58 |
| *10 years period* | | | | | | | | | | |
| 1995–2005 | 16 | 10 | 22 | 30 | 44 | 40 | 58 | 48 | 38 | 56 |
| 2000–2010 | 8 | 14 | 26 | 34 | 44 | 44 | 52 | 64 | 70 | 64 |
| *15 years period* | | | | | | | | | | |
| 1995–2010 | 12 | 18 | 30 | 40 | 56 | 52 | 54 | 58 | 64 | 58 |

2002 to 2003, $Px$ ($x=1, 2, 3, 4$) were identical. As $x$ increased, a greater variety of sectors appeared in $Px$. Over the 5-year time period, from 1995 to 2000, from 2000 to 2005 and from 2005 to 2010, for any given $x$, the participating sectors changed. This greater variety was also a characteristic observed in the 15-year time period, but the variations were more pronounced. Hence, one finding of the analysis is that the feedback loop structure changed as the time interval increased.

### 4.3 The structure and the linkage change analysis

To answer the question about which value chains of production have either relocated or disappeared and how this affected the complexity of the economic structure, structure and linkage change analysis was employed. Using the proportion change and point change analysis in Tables 2 and 3, we compared the structure and the linkage change during 15 years between 1995 and 2010. It would be impossible to effectively summarize all the changes for all the feedback loops so, by way of illustration, attention is focused on the first two feedback loops that accounted for the largest proportion of the total intermediate flows. The components of the first two feedback loops in 1995 and 2010 are shown in Table 5. Figures 2, 3, 4 and 5 are derived from the entries in Table 5.

Table 5 and Figs. 2 and 3 show that there were three subloops that involved more than two sectors in 1995 $T_1$. These subloops were integrated into one subloop after sector 16 and sector 32 joined, and some linkages changed in 2010 $T_1$ (see Fig. 3a and Table 6). In 1995 $T_1$, there were 23 self-dependent sectors. In 2010 $T_1$, the number changed to 21 since sectors 16 and 32 were no longer part of the self-dependent sectors set.

Figure 3a shows that sector 16 had new linkages with sector 4 and sector 36 in 2010 $T_1$. The new transaction from sector 4 to sector 16 was \$2813 m accounting for 9.1% of the 2010 $T_1$ intensity. This new linkage was strong, while its new linkage with sector 36 was very weak (the transaction was \$28.9 m). Similarly, sector 32 had new linkages with sector 18 and 10; their linkages were relatively modest as well (the transactions were \$216.2 m and \$28.6 m).

Table 6 shows that in terms of the change of linkage strength, the input from sector 30 to sector 4 increased 126.3% from 1995 $T_1$ to 2010 $T_1$ and their proportion of the $T_1$ intensity increased from 12.9% in 1995 to 26.2% in 2010. The input from sector 28 to sector 27 increased 80.1% from 1995 $T_1$ to 2010 $T_1$. The input from sector 27 to sector 30 increased 34%. These three increased transactions and the new transaction from sector 4 to sector 16 accounted for 83.5% of the intensity change of $T_1$ from 1995 to 2010. Sector 4 played an important role in the linkage and transaction change from 1995 to 2010. These feedback changes in $T_1$ reflected the important shift in intraregional transactions from manufacturing dominance to service–service interactions, although the process began in earnest a decade earlier.

Table 5 and Figs. 4 and 5 show that in 1995 $T_2$ and 2010 $T_2$, the two subloops that included more than four sectors were different, but the structures of the other subloops (included self-dependent subloops by sector 10 and sector 30) were the same. The proportion of each subloop to the total intensity of $T_2$ changed little.

Table 7 shows that for the change of linkage strength, the input from sector 27 to sector 4 increased 84.9% from 1995 $T_2$ to 2010 $T_2$ while the proportion of this interaction in $T_2$ increased from 16.9 to 27.7%. Its contribution to change of $T_2$ intensity was 28.8%. For the self-dependent sector 30, its transaction increased 56.5%, which contributed to 21.6% of the $T_2$ intensity change. The input from sector 28 to sector 34 increased 95.7%, which ranked the first, but the contribution to the $T_2$ intensity change was a more modest 9.2%. The increase in inputs from sector 4 to sector 27, from sector 14 to sector 12 and from sector 31 to sector 5 contributed to 8.7%, 7.5% and 7.0% to the $T_2$ intensity change, respectively. All of these linkages strength change accounted for 83.0% of the $T_2$ intensity change from 1995 to 2010.

**Table 5** Components of the first 2 feedback loops from 1995 to 2010

| Year | $T_1$ | $T_2$ |
|---|---|---|
| 1995 | (1) 18–31–28–27–30–4–18 (12,689.0, 45.4%) | (1) 27–4–27 (5983.2, 28.4%) |
| | (2) 11–10–36–13–3–11 (1448.5, 5.2%) | (2) 30–30 (4020, 19.1%) |
| | (3) 35–9–35 (13.3, 0.05%) | (3) 11–22–14–12–24–13–35–7–15–6–11(3218.6, 15.3%) |
| | (4) Sectors1, 2, 5, 6, 7, 8, 12, 14, 15, 16, 17, 19, 20, 21, 22, 23, 24, 25, 26, 29, 32, 33, 34 are self-dependent subloops (13,807.8, 49.4%) | (4) 34–29–28–34 (3075.4, 14.6%) |
| | | (5) 2–32–21–20–17–23–25–33–31–5–16–3–9–8–1–2 (3055.9, 14.5%) |
| | | (6) 19–18–19 (871.8, 4.1%) |
| | | (7) 10–10 (498.8, 2.4%) |
| | | (8) 36–26–36 (361.2, 1.7%) |
| 2010 | (1) 9–35–11–10–32–18–31–28–27–30–4–16–36–13–3–9 (23,152.4, 57.2%) | (1) 27–4–27 (9932.5, 31.4%) |
| | (2) Sectors 1, 2, 5, 6, 7, 8, 12, 14, 15, 17, 19, 20, 21, 22, 23, 24,25, 26, 29, 33, 34 are self-dependent subloops | (2) 11–22–14–12–24–13–35–31–5–16–3–11 |
| | (17,303.0, 42.8%) | (8236.4, 26.1%) |
| | | (3) 30–30 (6293.1, 19.9%) |
| | | (4) 34–29–28–34 (4577.1, 14.5%) |
| | | (5) 19–18–19 (904.2, 2.9%) |
| | | (6) 2–32–21–7–15–33–25–20–17–23–9–8–6–1–2(688.3, 2.2%) |
| | | (7) 10–10 (637.0, 2.0%) |
| | | (8) 36–26–36 (327.5, 1.0%) |

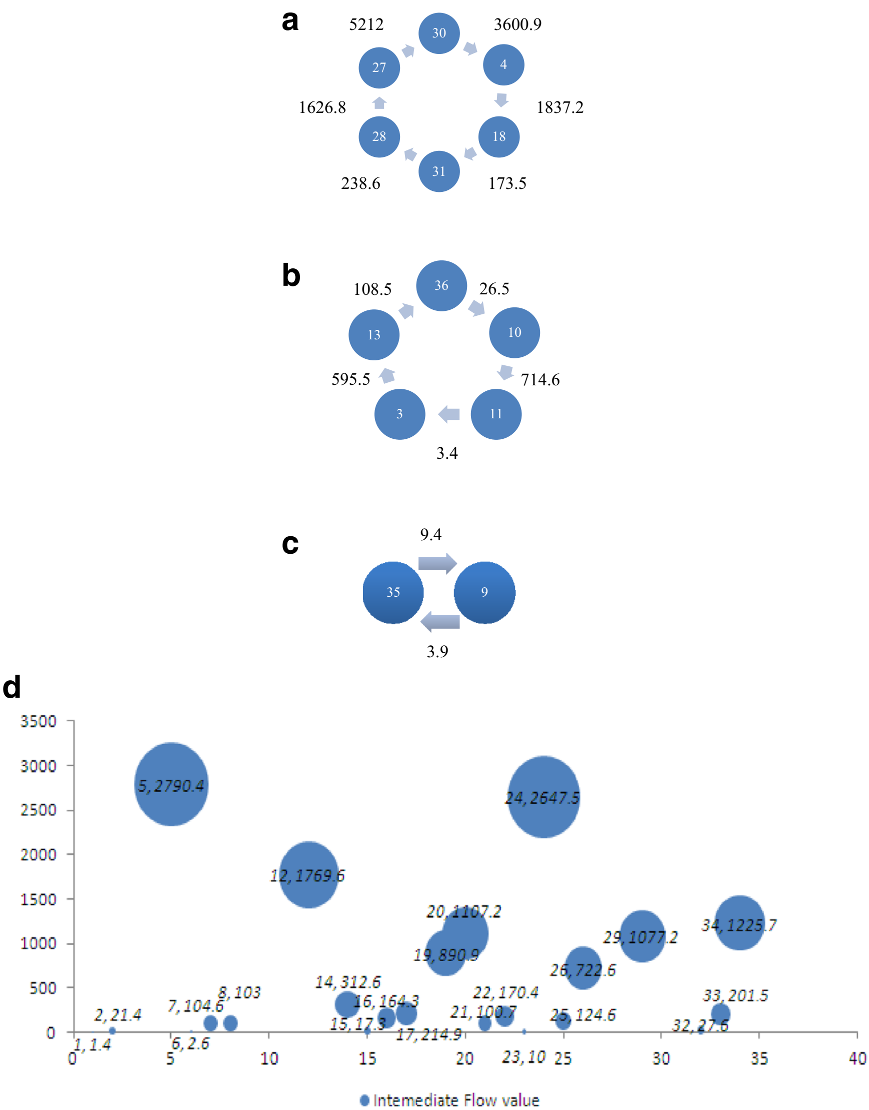


**Fig. 2** 1995 T1 structure. **a** Subloop 1 of 1995 T1, **b** Subloop 2 of 1995 T1, **c** Subloop 3 of 1995 T1 and **d** self-dependent subloops of 1995 T1

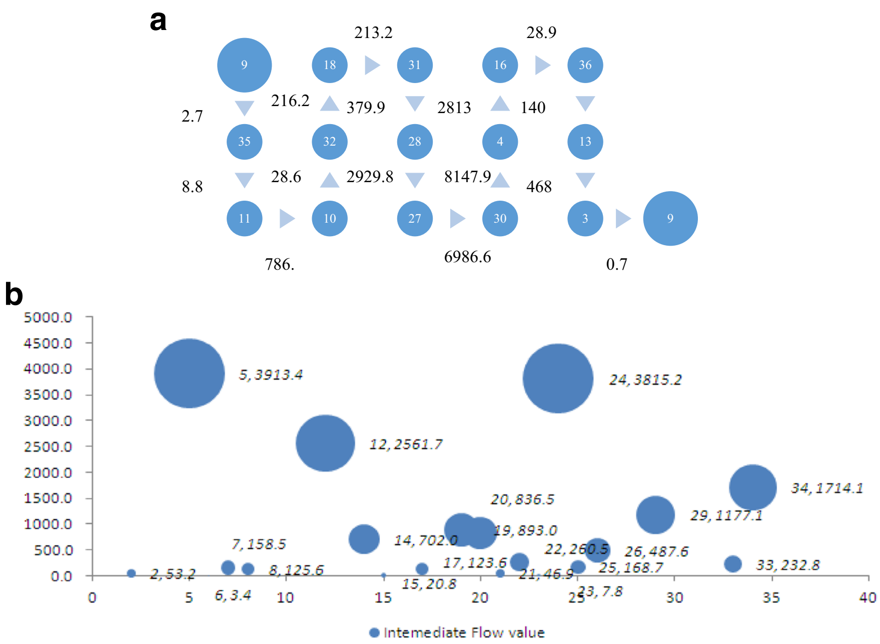


**Fig. 3** 2010 T1 structure. **a** Subloop 1 of 2010 T1 and **b** the other self-dependent subloops of 2010 T1

Some new linkages appeared such as input from sector 6 to sector 1 in 2010 $T_2$. Certainly, some linkages in 1995 $T_2$ disappeared in 2010 $T_2$ such as the input from sector 8 to sector 1.[3] However, these transactions were very weak (see Table 8).

These revealed that the changes of linkage strength from sector 27 to sector 4, from sector 28 to sector 34 and the others in Table 7 were the main sources of the complexity change from 1995 $T_2$ to 2010 $T_2$. The structural change of linkages played little role for the $T_2$ complexity change. The analysis of the first two feedback loops illustrates the different forces at work in Chicago's economic structural change from 1995 to 2010, with some sectors experiencing increased interaction while others decreased; some linkages strengthened while others weakened or disappeared. Since the interindustry transactions in the Chicago input–output table are essential intraregional trade flows, one would expect a greater degree of volatility here than in say a matrix of total [intra-, inter- and interregional as well as international (import) input flows] interindustry flows. As noted in the review of prior work, the forces generating these changes may have reflected changes in ownership patterns as firms sought to optimize production and flows across multiple establishments often located in different regions. This kind of analysis can be applied to the other 34

[3] The disappearance of a transaction in a feedback loop does not mean that the sectors no longer interacted; rather, it implies that its importance in the interindustry transactions had declined and thus was relegated to a lower feedback loop.

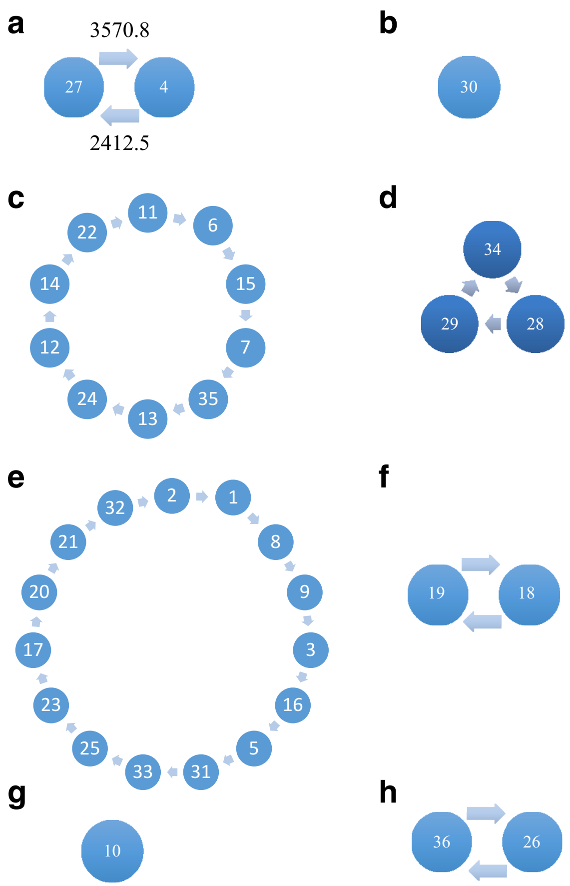


**Fig. 4** 1995 T2 structure. **a** Subloop 1 of 1995 T2, **b** Subloop 2 of 1995 T2, **c** Subloop 3 of 1995 T2, **d** Subloop 4 of 1995 T2, **e** Subloop 5 of 1995 T2, **f** Subloop 6 of 1995 T2, **g** Subloop 7 of 1995 T2 and **h** Subloop8 of 1995 T2

feedback loops. The Excel file of detailed 36 feedback loops was supplied as supplementary file to the journal.

The changes of $T_1$ and $T_2$ represented the main economic structure change of Chicago. These changes were certainly influenced by public policy. From 1989, when Richard M. Daley was elected as the mayor of Chicago, he proposed a more balanced economic development strategy. He stressed the importance of the central district to the development of the whole city region and thus actively promoted the construction of more office space and sought to enhance the competitive position of the financial industry. At the same time, attempts to expand and retain more traditional (manufacturing) industries continued. For example, in 1992, the municipal government issued \$160 million bonds, especially for the improvement in the infrastructure, in which \$50 million was set aside for infrastructure rebuilding. In 1994, the Model Industrial Corridors Initiative was enacted. \$1–1.5 million dollars was provided as a subsidy by the municipal government to help construct the local manufacturing district. In 1994, a TIF (Tax Increment Financing) district program was initiated; by 1997, there were 17 TIF districts. The new government planned

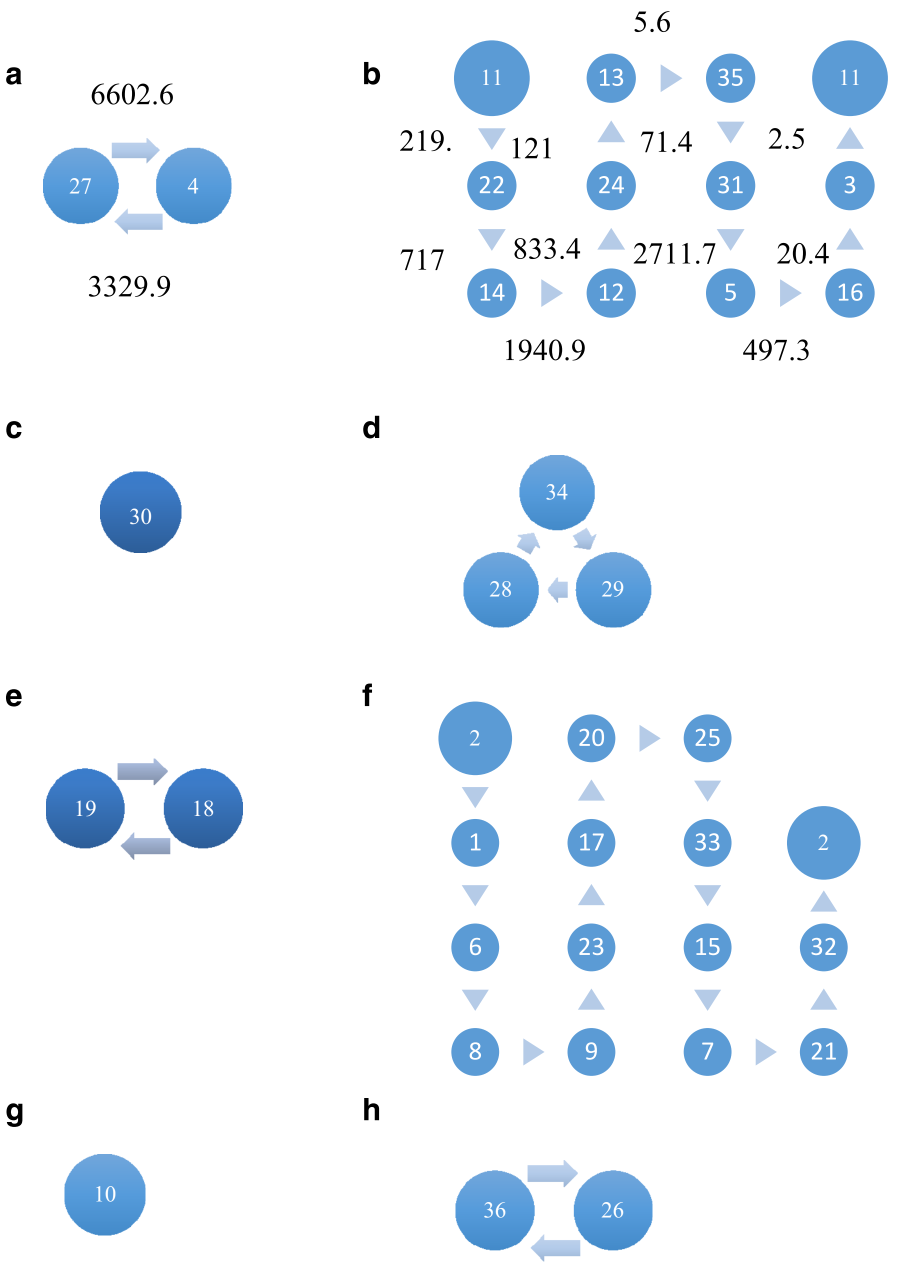


**Fig. 5** 2010 T2 structure. **a** Subloop 1 of 2010 T2, **b** Subloop 2 of 2010 T2, **c** Subloop 3 of 2010 T2, **d** Subloop 4 of 2010 T2, **e** Subloop 5 of 2010 T2, **f** Subloop 6 of 2010 T2, **g** Subloop 7 of 2010 T2 and **h** Subloop 8 of 2010 T2

**Table 6** Main linkage strength and their proportion change from 1995 T1 to 2010 T1

| | 28–27 | 27–30 | 30–4 | 4–16 | 4–18 |
|---|---|---|---|---|---|
| 1995 T1 | 1626.8 (5.8%) | 5212 (18.6%) | 3600.9 (12.9%) | 0 | 1837.2 (6.6%) |
| 2010 T1 | 2929.8 (9.4%) | 6986.6 (22.5%) | 8147.9 (26.2%) | 2813 (9.1%) | 0 |
| Change rate (%) | 80.1 | 34.0 | 126.3 | – | – |
| Change volume | 1303 | 1774.6 | 4547 | 2813 | – 1837.2 |
| Contribution to T1 intensity change (%) | 10.4 | 14.2 | 36.4 | 22.5 | – 14.7 |

In Table 5, 28–27 means the input from sector 28 to sector 27, the same to the others in Tables 5, 6 and 7

to strengthen Chicago's position as a network center for the financial, trade and transportation industries, develop business, trade, tourism, exhibitions, conferences industry and make these (more diversified set of) industries become the main pillar of the city's economy. With the stimulation of these policies, sectors 30, 4, 28 and sector 16 achieved outstanding performance in terms of growth. Because the margins paid by manufacturing and other goods industries were increased, sectors 27 developed rapidly. These industries are labor-intensive, and their development generated more in-migration to Chicago. In 1990s, Chicago gained 113,000 new inhabitants. Chicago gradually established a modern service-oriented diversified economy, including traditional manufacturing, modern manufacturing, traditional services and production services. In fact, Chicago became a service-dominated region 2 years before the USA as a whole. Sassen (2013) considered that Chicago's agro-industrial economy, and its associated financial and legal support services, toward international markets has allowed it to succeed in its transition to a knowledge economy. Romero et al. (2009) supported these findings by providing some complementary insights into the role of functional and spatial fragmentation in the Chicago region through a comparison over time of average propagation lengths.

## 5 Conclusions

In the present paper, hierarchical feedback loop analysis developed by Sonis and Hewings (1988, 1991) is employed to extract the detailed hierarchical feedback loops among 36 sectors every 5 years from 1995 to 2010. Attention is directed to the feedback loops that capture the main character of the economic structure transformation by highlighting changes in the structure and intensity of these loops. From these results, some additional, valuable insights were obtained into the process of economic development, particularly through changes in economic structure. A total of 36 hierarchical feedback loops for years 1995, 2000, 2005 and 2010 were obtained. The feedback loop structure had more changes as the time interval increased. The first two feedback loops represented the main character of the economic structure transformation. The input of sector 30, sector 27 and sector 4 was the three main and

**Table 7** Main linkage strength and their proportion change from 1995 T2 to 2010 T2

| | 27–4 | 30–30 | 28–34 | 4–27 | 14–12 | 31–5 |
|---|---|---|---|---|---|---|
| 1995 T2 | 3570.8 (16.9%) | 4020.1 (19.1%) | 1016.2 (4.8%) | 2412.5 (11.4%) | 1147.8 (5.4%) | 1979.8 (9.4%) |
| 2010 T2 | 6602.6 (27.7%) | 6293.1 (19.9%) | 1988.2 (6.3%) | 3329.9 (13.9%) | 1940.9 (8.1%) | 2711.7 (11.4%) |
| Change rate (%) | 84.9 | 56.5 | 95.7 | 38.0 | 69.1 | 37.0 |
| Change volume | 3031.8 | 2273 | 972 | 917.4 | 793.1 | 731.9 |
| Contribution to T2 intensity change (%) | 28.8 | 21.6 | 9.2 | 8.7 | 7.5 | 7.0 |

**Table 8** Linkage structure change and their transactions in 1995 T2 and 2010 T2

| | 6–1 | 8–6 | 9– 23 | 8–1 | 3–9 | 33–31 |
|---|---|---|---|---|---|---|
| 1995 T2 | 0 | 0 | 0 | 0.1 | 2.6 | 64.2 |
| 2010 T2 | 0.6 | 0.1 | 1.8 | 0 | 0 | 0 |

stable forces of the first two feedback loop intensities. The input of sector 5, sector 34, sector 28, sector 24 and sector 31 had much more change. The input from sector 30 to sector 4, from sector 28 to sector 27, from sector 27 to sector 30 and the new transaction from sector 4 to sector 16 accounted for 83.5% of the intensity change of $T_1$ from 1995 to 2010. The structural change of linkages played little role in the complexity change of $T_2$. The change of linkages strength from sector 27 to sector 4 and from sector 14 to sector 12 contributed to the most of the complexity changes from 1995 $T_2$ to 2010 $T_2$.

The experience of Chicago economic transformation showed that urban economic diversification is one of the keys in the creation of a healthy and more sustainable regional economy. Services and industry are not necessarily in competition; development of services does not necessarily mean the decline of industry. As Romero et al. (2009) revealed, in many cases the development of many components of the service industry represented outsourcing and fragmentation of production. Many of the industries remained, but their production systems changed with transactions moving from the main diagonal (intra-sectoral) to off-diagonal (inter-sectoral). These changes appear to be reflected in the feedback loop analysis. The results provide additional insights into the findings of Romero et al. (2009) suggesting that the increase in complication of some sectors could be identified in the changes in the structure of feedback loops as well as the changes in the intensity of interactions.

In addition, the availability of a more comprehensive interregional social accounting system could provide a more complete picture of the structure of transactions that extend beyond interindustry flows—capital, labor, flows of funds and so forth. It is possible that the structure of these more comprehensive flows might change the hierarchical structures revealed in the interindustry analysis. Notwithstanding these limitations, the method provides a useful overview of the process of economic development and, particularly, the way in which development is manifested through changes in economic structure.

The analysis in this paper focuses on one major metropolitan region, for which a time series of input–output tables is available; however, the methodology can be applied to other regions and countries.[4] With the new development in trade in value added (see for example, Imori et al. 2016), there exists the possibility of exploring differences over time in the feedback loops in gross and value-added terms.

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[4] The methodology will be added to the REAL IO toolbox (www.real.illinois/realio) and is freely available.

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## Affiliations

**Xiuli Liu[1,2,3] · Geoffrey J. D. Hewings[4]**

Geoffrey J. D. Hewings
hewings@illinois.edu

[1] Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Zhongguancun East Road No. 55, Beijing 100190, People's Republic of China

[2] University of Chinese Academy of Sciences, Beijing, 19 A Yuquan Rd, Shijingshan District, Beijing 100049, People's Republic of China

[3] Center for Forecasting Science, Chinese Academy of Sciences, Zhongguancun East Road No. 55, Beijing 100190, People's Republic of China

[4] Regional Economics Applications Laboratory, University of Illinois, 1301 W Gregory #236, Urbana, IL 61801, USA