A Network Analytic Approach to Analyzing Health Care Markets

Introduction

The analysis and oversight of health care markets often involves quantifying interactions among market participants. The influential Dartmouth Atlas, for example, draws on patient flow data from ZIP codes to hospitals to define the geographic boundaries of hospital service areas and referral regions. Data on shared patients among clinicians facilitate insights into practice patterns and the diffusion of medical technology and knowledge. Finally, antitrust enforcement efforts and research on market concentration draw on measures of market power based on predictions from patient demand systems and bargaining between providers and insurers.

While the above examples cover expansive ground in terms of their applications within health economics, they share a common thread in their use of relational data capturing economic and clinical ties within and among geographic locations and market actors. Fundamentally, we can think of these units and the ties among them in terms of a multidimensional "network" representing a health care economy. In this study, we formalize this observation by developing a network analytic approach for defining and analyzing health care markets.

Our approach provides several noteworthy contributions:

1. Formalize **market boundary** definitions to encompass widely used market definition methods (e.g., geopolitical and geographic boundaries, firm-specific catchment areas based on travel time/distance or patient flows.
2. Develp and apply **market composition** measures that quantify the degree to which a given market grouping measure captures relevant underlying clinical and economic activity (e.g., patient flows to hospitals, shared patients and referrals among clinicians and facilities, etc.).
3. Formalize **market concentration** measures and test whether providers with high market concentation values, or high willingness to pay values, are more likely to be included in provider networks.

Our network analytic framework is useful because it provides researchers and regulators with a formalized platform for measuring and testing market definitions based on underlying economic principles. The impetus for vertical integration, for example, is often to widen the reach of hospitals by capturing new referral networks. Our shared patient fraction measure provides a direct quantification of the extent to which an existing or hypothetical grouping of providers captures these underlying referral relationships. Similarly, WTP measures quantify the amount an insurer would be willing to pay to include a provider in its network. Providers with high WTP values dominate "micromarkets" defined by geographies and/or important clinical service lines–affording them significant bargaining power when negotiating network inclusion and prices. We demonstrate how our approach not only facilitates the application of WTP measures, but also provides a platform from which we can test whether providers with high estimated WTP are more likely to be included in insurance networks.

An application of our framework focuses on hospital markets in the state of Tennessee. Tennessee provides a useful setting because the eastern part of the state has been the focus of significant antitrust attention following the 2018 merger between Wellmont Health Systems and Mountain States Health Alliance. The resulting merged entity, known as Ballad Health, is the only inpatient treatment option for patients in the region. By comparison, as home to several large investor-owned hospital chains, a large academic medical center, a public hospital, and several not-for-profit hospital systems, the Nashville metropolitan area has one of the most competitive hospital markets in the entire U.S. We use our framework to delineate market boundaries within Tennessee, and to assess the degree to which these different market definitions capture underlying shared patient relationships and bargaining power for inclusion in small-group, individual market, and Medicare Advantage insurance networks.

Theory

Markets are often characterized by economic linkages among units defined by geographies and/or market actors. We will henceforth refer to these units as nodes.

We summarize these nodes V and the ties among them in a weighted graph:

$$G = (V, E, w)$$

In this representation, nodes V are joined by edges E, with edge weights w quantifying either the existence or strength of ties among nodes.

Health care markets are often (though not always) conceptualized in terms of directed linkages among disjoint sets of nodes. For example, market definitions are often based on patient flows and/or an underlying demand system (e.g., patients selecting hospitals). In that case, nodes refer to patient groups and hospitals, and edge weights reflect outputs from this system—such as observed or predicted hospital market shares for each patient grouping (e.g., based on residential geography, demographics, or conditions). Similarly, antitrust applications based on WTP quantify the amount an insurer would be willing to pay to include a provider in its network. These approaches model (1) bargaining between insurers and hospitals, and calculation of firm-specific WTP values are based on formulas that aggregate hospital choice probabilities among "micromarkets" defined by geographies (e.g., ZIP codes), patient attributes (e.g., race) and/or medical conditions (e.g., heart disease).

To account for these features, we extend the graph definition above to reflect a weighted directed bipartite graph:

$$G = (V_1, V_2, E, w)$$

The edges of this graph are defined such that each connects a node from V_1 to a node in V_2, and $V(G) = V_1 \cup V_2$, $V_1 \cap V_2 = \emptyset$. To extend the examples from above, elements in V_1 could correspond to different patient groupings (e.g., the residential ZIP code) and elements in V_2 correspond to hospitals. The graph is directed since weights based on patient flows or predicted demand originate from ZIP codes and terminate at different hospitals.

However the nodes V_1 and V_2 are defined, the bipartite graph representation (G) implies a rectangular incidence matrix $\mathbf{B}$. For example, if z is the number of ZIP codes and j is the number of hospitals, then the incidence matrix $\mathbf{B}$ is a $z \times j$ matrix with cells $B_{z,j}$. For $\mathbf{B}$, these cell values correspond to the total weight $w_{z,j}$ as defined above, and with cell values of zero indicating the absence of a tie between nodes.

Finally, based on this rectangular incidence matrix we also define a binary matrix $\mathbf{B}^*$, with cells equal to 1 if $w_{z,j} > 0$ and 0 otherwise.

Defining Market Structure

We next turn our attention to methods that delineate the structure health care markets. This structure may derive from disjoint geographic markets–for example, based on geopolitical or other boundaries such as the county, the metropolitan statistical area (MSA), or the commuting zone (CZ). Alternatively, we may wish to define overlapping firm-specific markets based on a fixed travel or distance radius, or by defining a variable market denominator based on some thresholding rule for patient inflows (e.g., the set of ZIP codes that supply at least 75% of a hospital's patients).

We will set aside for now the merits of these individual approaches, which are subject to any number of criticisms (Baker 2001), and simply formalize their application.

The delineation of market boundaries amounts to dividing the graph G into market subgraphs.

Network Analytic Measures

Define strength as

$$k_j = \sum_z B_{z,j}$$

$$k_z = \sum_j B_{z,j}$$

Market Definitions Based on Geographic and Geopolitical Boundaries

Firm-Specific Catchment Areas Based on Patient Flows

We define a function

$$G' = f(G, \tau) = (V, E', w)$$

where G' is a resulting bipartite graph that defines catchment areas for health care facilities. G is a weighted bipartite graph that maps geographic areas with a measure of flow (weights) to each health care facility. $\tau \in (0, 1)$ represent the thresholding applied to determine catchment areas.

$$G = (V, E, w)$$

Nodes in V_1 represent geographical areas, e.g. zip codes. V_2 represent health care facilities, e.g. hospitals. The set of edges $E = \{(x, y)|x \in V_1, y \in V_2\}$ connect V_1 to V_2. The weighting is a mapping $w : E(G) \to \mathcal{Z}_0$ which represents a flow of patients during the study period.

The resulting G' is a subgraph of G, where flows have been pruned that do not meet the threshold level τ. That is,

$$E' = \{(x, y)|(x, y) \in E \wedge w' \leq \tau\}$$

w' defines a function that given an edge returns the ordered normalized cumulative sum.

For normalizing the inbound flow we compute the total flow for use as a denominator,

$$n(v) : V_2 \to \mathcal{Z}_0 := \{(v, z)|z = \sum_{(x,v)\in E} w((x, v))\}$$

The prior cumulative normalized sum of an edge is defined as follows,

$$c(e) : E \to \mathcal{R} := \{((x, y), r)|r = \sum_{(i,y)\in E \wedge w((i,y))>w((x,y))} w((i, y))/n(y)\}$$

The final threshold is applied to this function resulting in the following:

$$E' : E \to E := \{e|c(e) \leq \tau\}$$

Note that in the case of ties definition includes all nodes that meet the threshold.

Firm-Specific Catchment Areas based on a Fixed Travel Time Radius

Community Detection (?)

Market Composition Measures

Modularity

Shared Patient Fraction

Market Concentration Measures

Geographic HHI Measures

There are two ways to define this:

1. **Outflow HHI**. From the perspective of the geographic location of patients, i.e., what is the HHI for a given ZIP code? This measure only considers market concentration in terms of patient flows originating *from* the geography:

$$HHI_z = \sum_j \left(\mathbf{S}_z \circ \mathbf{S}_z \right)$$

where geographic market shares are given by

$$\mathbf{S}_z = \text{diag}(1/k_z)\mathbf{B}$$

and $\circ$ is the Hadamard (element-wise) product.

2. **Inflow HHI**. From the perspective of the geographic location of hospitals, i.e., what is the HHI among hospitals located within a given geographic community c? This measure considers market concentration in terms of patient flows *into* the geography.

$$HHI_c = \sum_{j \in c} \left(\frac{k_j}{\sum_{j \in c} k_j} \right)^2$$

Firm-Specific HHI

$$HHI_j = \sum_z \left(\text{diag}(1/k_j)\mathbf{B}^T \text{diag}(HHI_z) \right)$$

$$HHI_z^{\text{firm}} = \sum_j \mathbf{S_z} \text{diag}(HHI_j)$$

Willingness-to-Pay

Capps et al (2003) show that bargaining power is a nonlinear function of patient choice probabilities:

$$W_i(J_h) - W_i(J_h - j) = -\ln \left(1 - s_{ij} \right)$$

Where s_{ij} is the probability of patient i selecting hospital j. If we aggregate patients into "micromarkets" m (e.g., by residential geography, patient demograhic groups, diagnosis, or some combination of these) we obtain:

$$WTP_j = -\sum_m N_m \ln\left(1 - \hat{s}_{mj}\right)$$

where N is the number of patients and $\hat{s}_{mj}$ is the predicted share of hosptial j in micromarket m.

$$WTP_j = -\sum_z \text{diag}(k_z)\mathbf{S}'_{\mathbf{z}}$$

where $\mathbf{S}'_{\mathbf{z}} = \ln(1 - \mathbf{S}_z)$.

Market	Hospitals Included	Geographies Included	H
Geographic-Outflow Method[1]			
geo_1	A, B	geo_1	
geo_2	A, B, C	geo_2	
geo_3	B, C, D, E, F	geo_3	
geo_4	C, D, E, F	geo_4	
geo_5	C, D, E, F	geo_5	
geo_6	C, D, E, F, G	geo_6	
geo_7	F, G, H, I	geo_7	
geo_8	J	geo_8	
geo_9	G, H, I, J	geo_9	
geo_10	H, I, J	geo_10	
Geographic-Inflow Method[2]			
M1	A, B, C	geo_1, geo_2, geo_3, geo_4, geo_5, geo_6	
M2	D, E	geo_3, geo_4, geo_5, geo_6	
M3	F, G, H, I	geo_3, geo_4, geo_5, geo_6, geo_7, geo_9, geo_10	
M4	J	geo_8, geo_9, geo_10	
Firm-Specific[3]			
A	A	geo_1, geo_2	
B	B	geo_1, geo_2, geo_3	
C	C	geo_2, geo_3, geo_4, geo_5, geo_6	
D	D	geo_3, geo_4, geo_5, geo_6	
E	E	geo_3, geo_4, geo_5, geo_6	
F	F	geo_3, geo_4, geo_5, geo_6, geo_7	
G	G	geo_6, geo_7, geo_9	
H	H	geo_7, geo_9, geo_10	
I	I	geo_7, geo_9, geo_10	
J	J	geo_8, geo_9, geo_10	
Firm-Specific - Aggregated to Geography[4]			
geo_1	A, B	geo_1	
geo_2	A, B, C	geo_2	
geo_3	B, C, D, E, F	geo_3	
geo_4	C, D, E, F	geo_4	
geo_5	C, D, E, F	geo_5	
geo_6	C, D, E, F, G	geo_6	
geo_7	F, G, H, I	geo_7	
geo_8	J	geo_8	
geo_9	G, H, I, J	geo_9	
geo_10	H, I, J	geo_10	

[1]Market shares defined as the share of patients from each geography who are treated at each hospital, regardless of the hospital's geographic location.
[2]Market shares defined as each hospital's share of total patients treated at hosptials located within the geographic market boundary (e.g., a county, MSA, etc.).
[3]Firm-specific HHIs are a weighted average of outflow-based geographic HHIs as defined above, with weights defined as the share of the hospital's total patients from each geography.
[4]Firm-Specific HHIs are aggregated to the geographic level using a weighted average of firm-specific HHIs. Weights are defined as the share of the geography's total patients who are treated at each hospital.

One-Mode Projection

When defining geographic or firm-specific markets, it is often useful to project the bipartite network G into a unipartite or single-node network $G_k = (V_k, E, w)$ that pairs similar vertex types.

As an example, consider the following incidence matrix representation of a network of $z = 10$ geographies and $j = 10$ hospitals, with cell values equivalent to the number of patients from a given geography who are treated at each hospital:

A one-mode projection into hospital pairings is given by $\mathbf{B}^T\mathbf{B_0}$, which yields the following $j \times j$ adjacency matrix $\mathbf{A_j}$

	A	B	C	D	E	F	G	H	I	J
A	23	23	12	0	0	0	0	0	0	0
B	27	44	30	17	17	17	0	0	0	0
C	81	150	458	377	377	377	95	0	0	0
D	0	52	181	181	181	181	32	0	0	0
E	0	393	1625	1625	1625	1625	429	0	0	0
F	0	93	388	388	388	487	194	99	99	0
G	0	0	85	85	85	193	313	228	228	120
H	0	0	0	0	0	116	220	316	316	200
I	0	0	0	0	0	52	94	163	163	111
J	0	0	0	0	0	0	178	358	358	383

This matrix quantifies the number of shared patient ties among hospitals. Importantly, the diagonal provides a summary count of the total number of patients treated in each hospital:

Hospital	total_patients
A	23
B	44
C	458
D	181
E	1625
F	487
G	313
H	316
I	163
J	383

Off-diagonal cells in this matrix provide information on the degree to which different hospitals draw patients from similar ZIP codes. For example, in the bipartite matrix **B** above we see that hospital A draws its 25 patients from two geographies, and hospital B draws its 59 patients from 3 geographies–two of which overlap with the geographies hospital A draws from.

In the one-mode projection matrix, the row pairing A with B tells us that all 25 of hospital A's patients are drawn from geographies it shares with hosptial B. And similarly, the cell pairing hospital B (row) with hospital A (column) tells us that 43 of hospital B's patients are drawn from geographies it shares with A.

We can similarly construct a $z \times z$ adjacency matrix $A_z = \mathbf{B}\mathbf{B_0}^T$

	geo_1	geo_2	geo_3	geo_4	geo_5	geo_6	geo_7	geo_8	geo_9	geo_10
geo_1	25	25	14	0	0	0	0	0	0	0
geo_2	25	106	94	81	81	81	0	0	0	0
geo_3	17	86	624	607	607	607	93	0	0	0
geo_4	0	97	658	658	658	658	82	0	0	0
geo_5	0	116	655	655	655	655	118	0	0	0
geo_6	0	95	651	651	651	736	180	0	85	0
geo_7	0	0	99	99	99	207	375	0	276	168
geo_8	0	0	0	0	0	0	0	25	25	25
geo_9	0	0	0	0	0	120	266	178	444	324
geo_10	0	0	0	0	0	0	165	180	345	345

This matrix provides useful information on shared hospitals among geographies. The diagonal tells us, for example, that 33 patients originate from `geo_1` and 43 originate from ZIP `geo_2`. The value in cell $A_z[1,2]$ tells us that all 33 of the patients from `geo_1` are treated in hospitals that overlap with those used by patients from `geo_2`, while the value in cell $A_z[1,3]$ shows that only 25 of these patients go to hospitals common with `geo_3`.

Application

```
## # A tibble: 3 x 3
##   group         medadv indiv
##   <fct>          <dbl> <dbl>
## 1 <5,000         0.678 0.552
## 2 5,000-10,000   0.812 0.615
## 3 10,000-20,000  0.852 0.6
```

```
## # A tibble: 1 x 3
##   group       medadv indiv
##   <fct>        <dbl> <dbl>
## 1 2,000-5,000  0.794 0.601
```

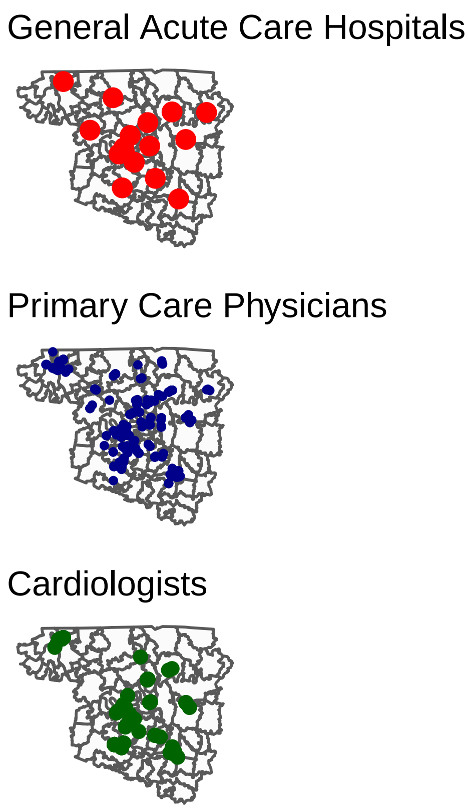

Figure 1: Geographic Location of Hospitals, PCPs and Cardiologists in Tennessee