

Nodes, Networks, and Net Worth

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Abstract

This article explores the integration of network theory into real estate valuation, proposing a potential “network valuation approach (NVA)” that complements traditional methods such as hedonic and spatial econometric models. The NVA differs by modeling value as a function of relational structure rather than isolated locational attributes, quantifying a property’s position and connectivity within physical, social, and economic networks using centrality measures. The approach develops a network value index (NVI) that captures value drivers through degree, closeness, and betweenness centrality metrics. A case study demonstrates the NVA’s practical application. This work illustrates how network connectivity influences value, suggesting an evolution in how appraisers conceptualize and assess market dynamics.

Introduction

The real estate valuation field is constantly evolving, adapting to the growing complexity of urban systems and the diverse ways in which properties generate value. Traditionally, the cost, sales comparison, and income capitalization approaches have been the cornerstones of appraisal practice, each providing unique perspectives. However, these approaches often fall short of fully capturing the intrinsic and interconnected aspects of a property’s value—that is, elements that arise from a property’s position within larger social, economic, and infrastructural networks, or those items traditionally thought of as linkages¹ to the professional appraiser. Is it possible we are missing key value components by focusing on properties as isolated entities?

This article introduces an early-stage exploration of what could be a fourth approach to valuation: a network valuation approach (NVA) inspired by network theory. Network theory, a discipline that studies the properties of intercon-

nected systems, offers tools and concepts that can be adapted to real estate valuation. By considering properties as nodes within various networks and analyzing their connections and positions, a more holistic and accurate assessment of their value can be developed.

Network theory offers an illuminating lens for understanding connectivity patterns. A compelling example emerges from the American Revolution, when Paul Revere and William Dawes embarked on similar midnight rides on horseback to warn of British troop movements. Despite sharing comparable backgrounds, their divergent legacies can be traced to their contrasting network positions. Revere’s enduring historical prominence stems not from superior individual qualities but from his role as what network theorists term as an “information broker.” While Dawes operated within more limited social circles, Revere had cultivated connections across diverse community groups, allowing his message to cascade through multiple social networks simultaneously.²

1. According to *The Dictionary of Real Estate Appraisal*, 7th ed. (Appraisal Institute, 2022), *linkage* is defined as: “1. Time and distance relationship between a particular use and supporting facilities, e.g., between residences and schools, professional services, shopping, and employment. 2. The movement of people, goods, services, or communications to and from the subject site, measured by the time and cost involved. 3. In land use planning, a positive or negative relationship among various land uses.” For this article, the terms *connection* and *linkage* are used consistently with this definition but in a broader sense to emphasize the networked relationships among external influences on property value.

2. Brian Uzzi and Shannon Dunlap, “How to Build Your Network,” *Harvard Business Review* (December 2005), <https://bit.ly/3WUT8XM>.

In valuation terms, this parallels how certain properties amplify their influence on surrounding land uses and value through location and function within economic networks.

This historical case underscores how network centrality measures and the strength of connections can amplify information flow and social influence far beyond what individual characteristics might predict. Similarly, understanding how a property's network position enhances or constrains its ability to transmit economic or social "signals" helps explain why two otherwise comparable assets can perform differently in the market.

This article is a work in progress, presented with the intent of sparking discussion, collaboration, and further refinement. The aim is to understand if and how networks affect those intrinsic yet crucial connections a property has with its surroundings and how they can be systematically quantified and included in appraisals. The proposal is driven by the belief that connectivity, both tangible and intangible, plays a pivotal role in determining a property's full value, something existing methods may inadequately capture.

A Brief History of Valuation Methods

The valuation of real property has been a cornerstone of economic activity and social organization for millennia. From the earliest forms of land ownership to the sophisticated appraisal methodologies of the twenty-first century, the determination of property value has evolved in response to changing societal needs, economic structures, and technological advancements.

The concept of assigning value to land and structures can be traced back to ancient civilizations. In ancient Egypt, for example, land surveys and assessments were conducted for taxation purposes, as evidenced by hieroglyphic records and the famed Rosetta Stone, which contains a decree about tax breaks.³ Similarly, the Roman Empire

developed a sophisticated system of property registration and valuation, largely driven by the need to administer its vast territories and collect taxes. The *Codex Theodosianus* and the *Codex Justinianus* provide insights into Roman property law and valuation practices.⁴

During the Middle Ages, land valuation in Europe was closely tied to the feudal system. Land was the primary source of wealth and power, and its value was often determined by its agricultural productivity and strategic importance. The Domesday Book, commissioned by William the Conqueror in 1086, stands as an example of a comprehensive land survey and valuation undertaken for taxation and administrative purposes.⁵

One method that is currently incorporated in the income capitalization approach was used as a stand-alone method for centuries. The concept of using rental value as a basis for determining the overall value of a property has ancient roots and was notably employed in various historical contexts. This is evident in Roman legal texts and property records, which often detail rental agreements and the income derived from properties.⁶

One of the earliest known papers on valuation is Sir William Petty's "Treatise of Taxes and Contributions." Petty explored various methods for assessing the value of land and assets, including considerations of rental income and potential productivity. He proposed that the value of land was equivalent to a certain number of years' worth of its annual rental income, one of the earliest uses of the rental value method.⁷

The eighteenth and nineteenth centuries saw further advancements in valuation theory and practice. In *An Inquiry into the Nature and Causes of the Wealth of Nations*, Adam Smith discussed the concept of value in relation to land and its productive capacity as well as the influence of market forces on prices.⁸ David Ricardo's work on rent theory, particularly his book *On the Principles of Political Economy and Taxation*, provided further insights into the relationship between land value, productivity, and economic rent.⁹

3. James Henry Breasted, *Ancient Records of Egypt* (University of Chicago Press, 1906), 253.

4. Barry Nicholas, *An Introduction to Roman Law* (Clarendon Press, 1962), 269–280.

5. H. C. Darby, *Domesday England* (Cambridge University Press, 1986), 208–211.

6. Nicholas, *Introduction to Roman Law*, 152.

7. William Petty, *A Treatise of Taxes and Contributions* (N. Brooke, 1662), 21–24, 31.

8. Adam Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations* (W. Strahan and T. Cadell, 1776), Chapter XI.

9. David Ricardo, *On the Principles of Political Economy and Taxation* (John Murray, 1817), 18–20, 29–30.

A historical method of real property valuation that was used for certain types of properties was the “profits method.” The profits method involved estimating the value of a property based on the profits generated by the business operating within it. This method was often applied to properties such as hotels, public houses (pubs), theaters, and other leisure or hospitality establishments where the income and consequently the value of the property were heavily dependent on business operations. The underlying assumption was that the value of such properties could be determined by analyzing the profitability of the businesses they housed.¹⁰

The late nineteenth and early twentieth centuries witnessed the professionalization of real estate appraisal, which was driven by several factors. The growth of cities and industries led to more complex real estate markets and increased demand for accurate valuations. As mortgage financing became more common, lenders required independent appraisals to assess collateral value. Additionally, governments increasingly relied on property valuations for taxation, eminent domain, and other public purposes.

In the United States, the formation of professional appraisal organizations, such as the American Institute of Real Estate Appraisers (AIREA) in 1932 (now part of the Appraisal Institute), played a crucial role in establishing standards and ethical guidelines for the profession. Frederick Babcock’s seminal 1932 work, *The Valuation of Real Estate*,¹¹ became a foundational text for the appraisal profession. It first stated that there is but one theoretically correct method of valuation, described as follows:

The theoretical method of valuation commences by studying the future utility of the property—that is, by forecasting the returns to be expected from the entire

productive unit, the returns to land being residual under the highest and best use, and the building returns, if the building is not the highest and best use, being made residual after the land return. The method proceeds, by discounting, to a calculation of present value of the net value of the net returns, the building returns being for a finite building lives, and the land returns being extended to perpetuity. In the method, the building value is so determined that the predicted building return provides both interest and a return of the capital value over the building life. Rates are determined on the market.¹²

Later in the text, the three traditional approaches to value—cost, sales comparison, and income capitalization—are outlined.¹³

The “contractor’s method,” also known as the cost approach in modern appraisal practices, has historical roots that can be traced back to the late nineteenth and early twentieth centuries. This method involves estimating the value of a property by calculating the current cost to construct a new building with the same utility, then deducting for depreciation and adding the value of the land.

One of the earliest proponents of this method was Irving Fisher, an influential American economist. Fisher’s work in the early twentieth century, particularly his ideas on capital and income, contributed to the theoretical underpinnings of the cost approach. He emphasized the relationship between the cost of production and value, which is a fundamental aspect of the contractor’s method.¹⁴

The mid-twentieth century saw further refinement of appraisal methodologies and a growing emphasis on standardization. The development of discounted cash flow (DCF) analysis, a more sophisticated form of income capitalization, gained prominence, particularly for valuing income-producing properties.¹⁵

10. Douglas Scarrett, *Property Valuation: The Five Methods* (Routledge, 1991), 81, 139–144.

11. Authors’ comment: It is well known that Frederick Babcock, a figure in the development of real estate appraisal practices, has been associated with racial statements and policies during his career. He played a key role in creating the Federal Housing Administration’s 1936 *Underwriting Manual*, which explicitly linked neighborhood desirability and property values to racial and socioeconomic composition. This article quotes this source only to reflect the germination of the approaches to value.

12. Frederick Morrison Babcock, *The Valuation of Real Estate* (McGraw-Hill, 1932), 165.

13. Babcock, *Valuation of Real Estate*, 167.

14. Irving Fisher, *The Theory of Interest* (Macmillan, 1930), 15.

15. Fisher, *Theory of Interest*, 15.

Has Valuation Kept Pace?

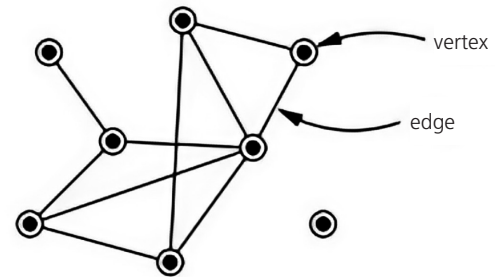
The growing complexity of urban environments has introduced dynamics that traditional valuation methods struggle to fully encapsulate. Factors like proximity to essential infrastructure, integration into smart city technologies, access to public amenities, and the evolving preferences of residents for walkable, mixed-use neighborhoods create value beyond what conventional metrics capture. For example, a property's value is not only a function of its physical attributes or recent comparable sales. Instead, its connectivity and role within a broader urban network significantly influence market perception and utility. The shift towards more sustainable, technology-integrated urban living amplifies these interdependencies, making it essential to adopt valuation methods that can quantify not only tangible but also intrinsic and synergistic value drivers. Thus, a new approach to valuation is crucial to more accurately reflect the realities of the modern property market, guiding informed decision-making for investors, developers, and policymakers alike. This historical progression reveals that each generation of valuation methods arose in response to new ways that properties created and exchanged value. The proposed network valuation approach follows in that tradition, extending appraisal logic into the era of data connectivity and relational economics.

Network Theory: An Overview

Network theory is an interdisciplinary field that examines how the interconnections between entities influence the behavior and elements of the entire system. Originating from graph theory in mathematics, it has expanded to include applications in sociology, computer science, biology, and physics.¹⁶ In network theory, entities are represented as nodes or vertices, and the connections between them are edges, as shown in Figure 1. The structure and dynamics of these networks can profoundly affect the nodes within them.

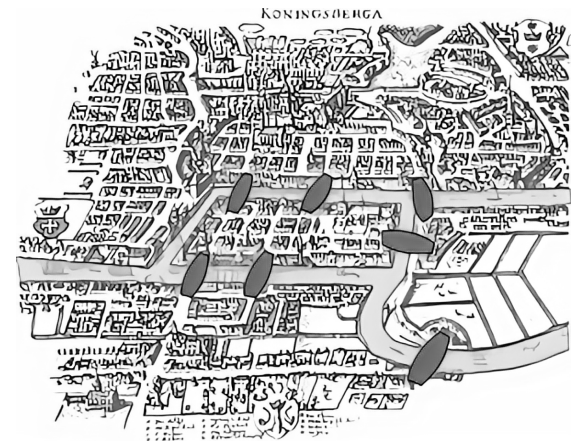
The story of Euler's solution to the Seven Bridges of Königsberg problem serves as an ele-

Figure 1. Vertices and Edges in Network Theory



Source: David Condrey - Own work, CC BY-SA 3.0, <https://bit.ly/4oFP2is>.

Figure 2. The Seven Bridges of Königsberg



Source: Bogdan Giușcă - Public domain (PD), based on the image, CC BY-SA 3.0, <https://bit.ly/4abkvo4>.

gant introduction to the fundamental concepts of graph theory and network analysis, which can be seamlessly connected to modern applications like Metcalfe's Law. This narrative journey through mathematical history and its contemporary relevance unfolds as follows.

Graph theory can trace its roots back to 1736, when the mathematician Leonhard Euler tackled an intriguing puzzle posed by the mayor of the Prussian city of Königsberg: Could one walk through the city crossing each of its seven bridges (shown in Figure 2) exactly once?¹⁷

16. "Network Theory," Wikipedia, last modified August 26, 2024, <https://bit.ly/4oQ1JXK>.

17. Kurt Kohlstedt, "The Seven Bridge Problem: How an Urban Puzzle Inspired a New Field of Mathematics," 99% Invisible, accessed December 3, 2024, <https://bit.ly/4okFMzh>.

Euler's approach to this problem was revolutionary. Instead of focusing on the physical layout of the city, he abstracted the problem into a mathematical structure we now recognize as a graph.¹⁸

Euler's abstraction laid the foundation for graph theory by introducing two key concepts:

1. **Vertices (nodes):** In Euler's model, the landmasses of Königsberg became vertices. In modern graph theory, a vertex or node is the fundamental unit from which graphs are formed.
2. **Edges:** The bridges connecting the landmasses were represented as edges. An edge in graph theory is simply a connection between two vertices.

This abstraction allowed Euler to focus on the essential elements of the problem: the connections between locations, rather than their physical attributes or distances. Euler's analysis of the Königsberg problem led him to develop what is now called graph theory, which has become a crucial tool in understanding networks.

In modern terms, we can define a graph G as a set containing two sets: vertices (V) and edges (E).

$$G = V, E$$

This mathematical representation allows for an analysis of complex networks, from social connections to computer systems, using the same fundamental principles Euler applied to the bridge problem.

Fast-forward to the digital age, and we find Metcalfe's Law, which builds upon the concepts Euler introduced. Metcalfe's Law states that as the number of nodes in a network grows, the potential connections between them grow exponentially. Under this concept, "a network becomes more valuable as it reaches more users."¹⁹ This concept has a clear connectivity to real estate. The formula for the number of possible connections in a network with n nodes is:

$$\text{Connections} = \frac{n(n-1)}{2}$$

The connection between Euler's work and Metcalfe's Law is insightful. Just as Euler abstracted a physical city into a graph, we can abstract modern networks (social media, marketplaces, communication systems, real estate) into nodes and edges/connections. Euler's insight that the key to the bridge problem lies in the connections rather than the physical layout parallels Metcalfe's focus on the value of connections in a network. The graph theory Euler pioneered provides the appropriate mathematical language to describe and analyze the networks to which Metcalfe's Law applies.

In essence, Euler's solution to a seemingly simple problem about bridges laid the groundwork for understanding complex networks that dominate our modern world. From social media platforms connecting billions of users to online marketplaces linking buyers and sellers globally, the principles Euler uncovered and codified in Metcalfe's Law continue to shape our understanding of networked systems and their exponential growth in value and complexity. Ruminating on this concept, an idea struck that there could be relevance and applicability to real estate valuation. For example, Figure 3 clearly shows that as the number of nodes increases, the connections increase substantially. If we consider the starting point or node as the subject property and consider all the possible linkages that could affect the value of the property, are we accounting for all those connections or linkages? Do our modern valuation approaches capture all these connections?

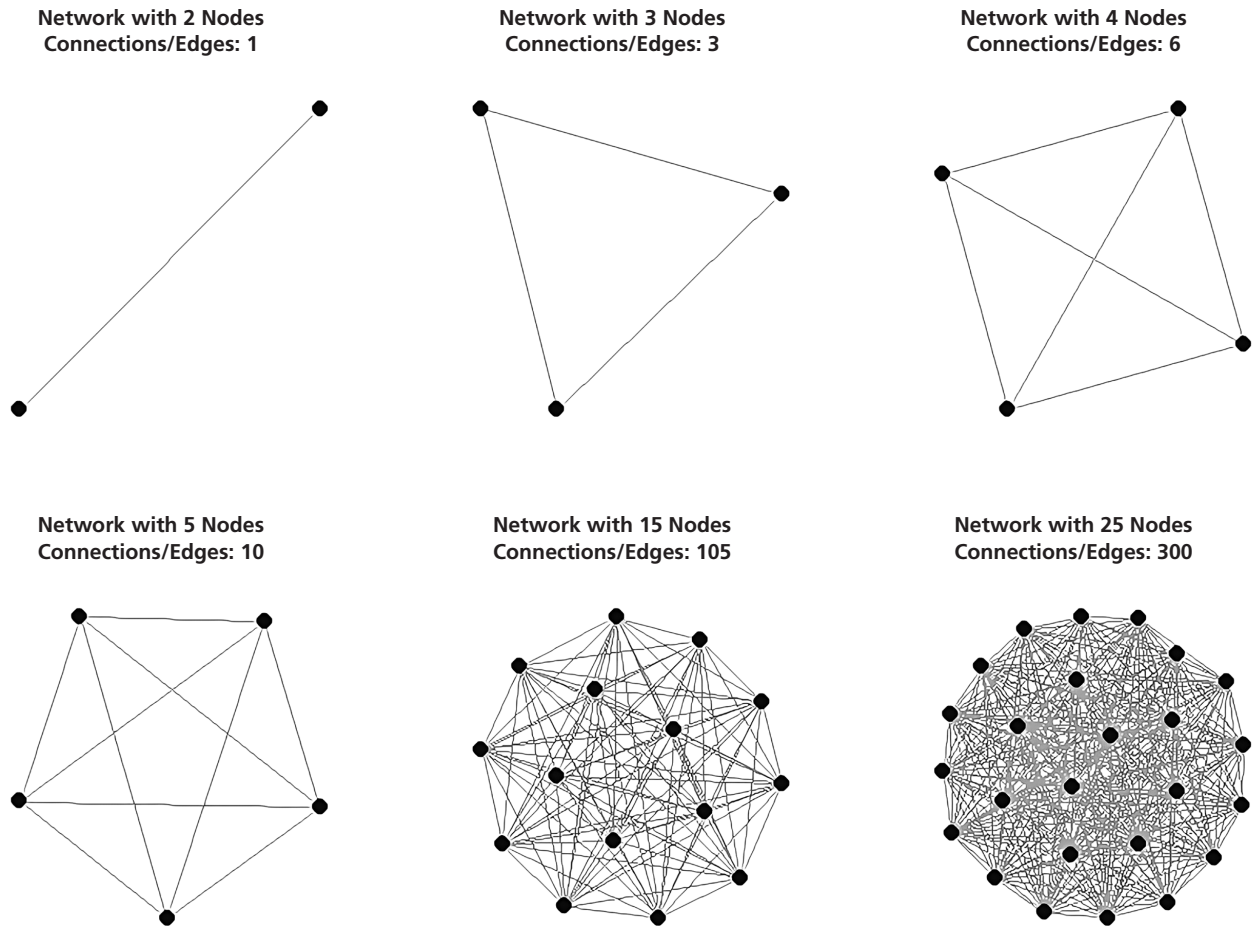
The Limitations of Traditional Valuation Methods

The traditional valuation methods have served the industry well but are not without limitations. According to *The Appraisal of Real Estate*,

In the cost approach, appraisers compare the replacement cost of the subject improvements to the cost to develop similar improvements as evidenced by the cost of construction of substitute properties with the similar utility as the subject property. The estimate of develop-

18. Kohlstedt, "The Seven Bridge Problem."

19. Robert M. Metcalfe, "Metcalfe's Law: A Network Becomes More Valuable as It Reaches More Users," *InfoWorld* 17, no. 40 (October 2, 1995): 53, Gale Academic OneFile (accessed November 27, 2024), <https://bit.ly/3K815XK>.

Figure 3. Networks with Nodes and Connections

ment cost is adjusted for market-extracted losses in value caused by the age, condition, and utility of the subject improvements or for locational problems. The land value as if unimproved is then added, usually based on comparison with sales of comparable sites with the same or a similar highest and best use. The sum of the value of the land and the improvements is adjusted for any existing property rights (e.g., leased fee, leasehold interests) included with the subject property.²⁰

While the cost approach is a cornerstone in appraisal practice, particularly for unique or newly constructed properties, it has constraints. These challenges, rooted in the methodology's reliance

on theoretical assumptions and market variabilities, highlight the importance of careful application and professional judgment.

A critical limitation of the cost approach is its potential divergence from market value. The cost to construct a property may not align with its market value due to variations in supply and demand, buyer preferences, and broader market conditions. For instance, market participants might perceive a newly constructed property's value differently based on its location, economic utility, or market trends, independent of its construction cost. According to *The Appraisal of Real Estate*, "The principle of externalities states that

20. *The Appraisal of Real Estate*, 15th ed. (Appraisal Institute, 2020), 525.

factors external to a property can have either a positive or negative effect on its value.”²¹

Accurately estimating depreciation poses a significant challenge in applying the cost approach. Depreciation includes:

1. Physical deterioration
2. Functional obsolescence
3. External obsolescence

While physical deterioration can sometimes be assessed objectively, functional and external obsolescence require subjective evaluation and market insight. For example, a property that has outdated features or is situated in an economically declining area might face depreciation factors that are complex to quantify and susceptible to variability.

Another limitation arises in the estimation of land value. In the cost approach, the land is valued separately, often using comparable sales. However, in markets with limited land transactions or unique parcels, finding truly comparable sales can be difficult. This lack of reliable data can introduce inaccuracies, undermining the credibility of the overall valuation.

For properties with highly specialized or unique uses, the cost approach can produce less reliable results. The cost to reproduce or replace the property may not align with its market utility or potential income generation. For example, older industrial facilities or purpose-built properties may not retain their original economic value, even if replacement costs remain significant.

Adjusting for market conditions, such as inflation or deflation in labor and material costs, introduces another layer of uncertainty. Fluctuating construction costs, availability of materials, and labor market conditions can complicate the accuracy of replacement cost estimates. Furthermore, the approach’s reliance on accurate and current data underscores the risk of inaccuracies when appraisers rely on outdated or inconsistent cost information.

As properties age, the reliability of the cost approach diminishes. Depreciation becomes a more substantial component of the valuation, increasing the difficulty of accurately reflecting the property’s condition and remaining economic

life. This makes the method less suitable for older properties or those undergoing significant functional changes.

Despite its limitations, the cost approach remains a valuable tool, particularly for appraising new construction or unique properties or when market or income data is insufficient. Its strength lies in providing a foundation for value when other approaches are not applicable. However, appraisers must exercise professional judgment, ensuring they recognize and mitigate these inherent limitations during its application.

Thus, while useful for new or unique properties, the cost approach’s limited consideration of network context underscores the need for a relational framework.

The Appraisal of Real Estate says the following about the sales comparison approach:

In the sales comparison approach, an opinion of market value is developed by comparing properties similar to the subject property that have recently sold, are listed for sale, or are under contract (i.e., for which a purchase offer and a deposit have been recently submitted). A major premise of the sales comparison approach is that an opinion of the market value of a property can be supported by studying the market’s reaction to comparable and competitive properties.²²

Like any appraisal methodology, the sales comparison approach is subject to certain limitations that can affect its accuracy and applicability. These limitations, rooted in the availability and reliability of data and the subjective nature of adjustments, necessitate careful consideration in professional practice.

The cornerstone of the sales comparison approach is the availability of comparable sales data. In markets with abundant, recent, and similar transactions, the approach performs well. In thin or specialized markets (e.g., historic or rural assets), comparables may be scarce.

Even when comparable sales are available, two properties are rarely identical. Variations in physical characteristics, location, size, and condition require appraisers to adjust the sale prices of comparables. These adjustments, while guided by market analysis and professional judgment, can be

21. *The Appraisal of Real Estate*, 15th ed., 28.

22. *The Appraisal of Real Estate*, 15th ed., 351.

inherently subjective and may introduce biases or inaccuracies. The use of paired sales or other techniques may help reduce subjectivity in some cases.

The sales comparison approach performs best in a relatively stable market where recent transactions reflect current market conditions. In volatile or rapidly changing markets, comparable sales may quickly become outdated, leading to valuations that do not reflect the present circumstances. For example, in a market experiencing rapid inflation or deflation, sales from even a few months prior may not be reliable indicators of current value.

Adjusting for differences between the subject property and comparables is one of the most critical yet subjective aspects of the sales comparison approach. Adjustments for factors such as location, amenities, or condition often rely on judgment or less precise data sources, which can lead to inconsistent results. Furthermore, the lack of a standardized adjustment methodology across appraisers can introduce variability into valuations.

The sales comparison approach places significant emphasis on recent transactions, potentially overlooking broader market trends or the future potential of the subject property. This can be a limitation in markets with speculative activity or significant anticipated changes in demand. This is a common criticism of appraisers who look at past transactional data without also performing serious forward-looking market analysis. This is an essential step in mirroring the actions of buyers who are looking to the future.

Despite its limitations, the sales comparison approach remains a valuable tool in real estate appraisal, particularly for residential properties and markets with abundant transaction data. Its strength lies in its intuitive appeal and grounding in actual market behavior. However, appraisers must recognize the inherent constraints of the method and exercise caution with unique properties or in markets with limited data or rapidly changing conditions. Like the cost approach, the sales comparison approach may overlook the unique network connections that enhance a property's value beyond its physical attributes.

The Appraisal of Real Estate explains the income capitalization approach as follows:

The income capitalization approach to value consists of methods, techniques, and mathematical procedures that an appraiser uses to analyze a property's capacity to generate benefits (i.e., usually the monetary benefits of periodic income and reversion from a future sale) and convert these benefits into an indication of present value.²³

Like the other two approaches to value, the income capitalization approach is not without its limitations. Reliance on assumptions about future income, market trends, and property performance introduces potential challenges that appraisers must navigate with caution.

The accuracy of the income capitalization approach depends heavily on reliable income and expense data. Errors or omissions in the calculation of gross income, vacancy rates, or operating expenses can significantly affect the valuation. For instance, underestimated maintenance costs or overestimated rental income can lead to inflated property values.

Estimating market rents and operating expenses involves analyzing comparable properties and market trends. In fluctuating or uncertain markets, these estimates may not accurately reflect future conditions. For example, a property's rental rates may decline due to increased competition or economic downturns, rendering initial projections overly optimistic.

The income capitalization approach requires assumptions about the future performance of the property, including income growth, vacancy trends, and capitalization rates. These projections, while grounded in market evidence and expectations known to participants as of the valuation date, remain subject to uncertainty. While appraisers and market participants cannot put a price on unforeseen or unexpected events, such events highlight the inherent risk that actual outcomes may diverge from those anticipated in the valuation.

One of the most subjective elements of the income capitalization approach is the selection of an appropriate capitalization rate. The capitalization rate reflects the risk and return expectations of investors, and small variations in its determination can lead to significant differences in value estimates. For example, if the selected rate does

23. *The Appraisal of Real Estate*, 15th ed., 413.

not adequately account for property-specific risks or market conditions, the resulting valuation may not align with investor perceptions.²⁴

While the income capitalization approach is well-suited for standard income-producing properties, it is less effective for properties with unique characteristics or non-traditional income streams. Properties such as cultural institutions, government buildings, or those with heavily subsidized rents may not fit the traditional income models assumed by the approach.

In volatile markets, the income capitalization approach's reliance on current and projected income streams can introduce significant uncertainty. Rapid changes in interest rates, inflation, or local economic conditions can render capitalization rates and income projections obsolete, leading to inaccurate valuations.

When appraisers use a more detailed DCF analysis within the income capitalization approach, the complexity increases. DCF involves forecasting income and expenses over multiple years, then discounting those cash flows to their present value. While this method provides a nuanced valuation, it amplifies reliance on accurate projections and market data, making the analysis vulnerable to errors in forecasting or incorrect discount rate selection.

The income capitalization approach focuses on income generation, making it less applicable for properties not primarily intended to produce income, such as owner-occupied residential or commercial buildings. In such cases, the approach may fail to capture the property's value accurately.

Despite these limitations, the income capitalization approach remains a cornerstone of real estate valuation for income-producing properties. Its strength lies in its ability to align valuations with investor perspectives and market realities. In a continuing theme, the income capitalization approach may not fully account for how network effects influence a property's value.

The three traditional valuation methods—cost, sales comparison, and income capitalization—tend to evaluate properties in isolation, emphasizing individual characteristics and immediate

financial metrics. They often fail to systematically consider how a property's position within social, economic, and infrastructural networks enhances or diminishes its value. This oversight can lead to undervaluation or overvaluation, misinforming investors, developers, and policymakers. Each of the traditional valuation approaches captures important dimensions of value, yet all three are grounded in the treatment of properties as discrete, self-contained entities. The network valuation approach responds to this limitation by viewing properties as interdependent nodes within larger spatial, social, and economic systems. This perspective allows appraisers to account for the structural relationships that traditional methods acknowledge qualitatively but rarely quantify.

Applying Network Theory to Real Estate Valuation

By applying network theory to real estate valuation, we can model properties as interconnected nodes within multiple overlapping physical, social, economic, and environmental networks. Properties are not isolated assets but are embedded within a complex web of connections that significantly influence their value.

In the physical or infrastructural network, properties are connected through transportation infrastructure, utilities, and communication systems as examples. Proximity to highways, public transit, and airports enhances accessibility, while connections to traditional utilities and high-speed internet increase utility and desirability. In the social network, properties are linked through relationships among residents, community organizations, and social institutions. Strong social networks can increase property values through improved community support and shared resources.

The economic network encompasses the flow of goods, services, labor, and capital. Properties located in thriving districts benefit from economic activities generated by surrounding businesses, enhancing their income potential and

24. Appraisers seeking current capitalization rate benchmarks can reference several industry-standard sources. RealtyRates.com provides quarterly surveys by property type and market. PwC and the Urban Land Institute publish annual investor sentiment data in *Emerging Trends in Real Estate*. Major brokerage firms including CBRE, JLL, Cushman & Wakefield, Colliers, and Marcus & Millichap regularly release market-specific capitalization rate reports. CoStar and MSCI Real Assets also maintain comprehensive databases of transaction-based capitalization rates.

overall value.²⁵ Environmental networks consider ecological systems and green spaces, connecting properties through shared environmental resources that contribute to quality of life.

For example, a property located in a flourishing business neighborhood gains from the economic performance generated by surrounding businesses. Traditional methods may capture this through higher income potential but may not fully account for the synergistic effects of being part of a dynamic economic hub. Similarly, properties within close-knit communities or areas with strong social cohesion can have increased desirability due to factors like a sense of belonging, community support, and shared resources. These intrinsic benefits are hard to quantify using traditional methods. Finally, proximity to transportation networks, utilities, and digital infrastructure (like high-speed internet) significantly impacts a property's utility and value. While location adjustments are made, they may not fully reflect the enhanced value from being highly connected.

Moreover, as urban environments become more complex and interdependent, the interactions between properties and their networks intensify. Factors such as walkability scores, access to shared services, and digital connectivity become increasingly important to buyers and tenants.

The lack of a systematic approach to incorporate these network effects leads to valuations that may underestimate or overlook critical aspects influencing a property's value. This can result in the mispricing of assets, and investors may miss opportunities or take unintended risks due to incomplete valuation data. There could be an inefficient resource allocation where developers and policymakers might not prioritize areas where network enhancements could yield significant value increases. Furthermore, communities lacking network connectivity may remain undervalued and underinvested, perpetuating cycles of neglect and loss of wealth build-

ing and possibly resulting in social inequities.

Addressing this challenge requires integrating a framework that methodically analyzes and quantifies the network effects on property value.

Centrality Measures in Real Estate

Centrality measures from network theory can be adapted to assess a property's importance within its networks. There are three primary measures that have applicability: degree centrality, closeness centrality, and betweenness centrality.²⁶

Degree Centrality

Degree centrality is defined as a measure of the number of direct connections to a node.²⁷ In traditional network theory, networks can be directed (where connections have directions) or undirected (where connections can easily flow back and forth and are not limited to one-way flow). For this article, undirected networks are the proper analogue for real estate markets where consumers and users of real estate can easily flow from one property to another.

For the purposes of this article, degree centrality quantifies the number of direct connections a property has with key nodes such as schools, hospitals, transit stations, and commercial centers. Properties with higher degree centrality are often more desirable due to increased convenience and accessibility. To calculate the degree centrality, the following formula can be used:

Degree centrality:²⁸

$$C_D(v) = d(v)$$

Where:

- $C_D(v)$ is the degree centrality of node v
- $d(v)$ is the degree of node v , which represents the number of direct links to v

25. According to *The Dictionary of Real Estate Appraisal*, 7th ed., this concept is described as the law of cumulative attraction, defined as "A principle that recognizes that a retail property's location in a retail cluster of similar but not identical retailers attracts more customer traffic than a stand-alone location would.," 46.

26. There are many types of network centrality measures, including degree, closeness, betweenness, Eigenvector, Katz, and harmonic centralities as well as PageRank and eccentricity. The three measures the authors found most useful for real estate have been used herein.

27. Ernesto Estrada, "Centrality in Networks: Finding the Most Important Nodes," in *Business and Consumer Analytics: New Ideas*, ed. Pablo Moscato and Natalie Jane de Vries (Springer Nature, 2019), 404, Section 8.3.1.

28. "Centrality," Wikipedia, last modified November 29, 2024, <https://bit.ly/49DFpMy>. Note that sometimes the $d(v)$ is shown as $deg(v)$.

For example, if you have a simple undirected network with five nodes (A, B, C, D, E),

- Node A has connections to Nodes B, C, and D.
- The degree centrality of Node A would be $d(A) = 3$ (as shown in Figure 4).

As shown, this measure is easy to calculate but has some limitations when used alone. For example, different networks often have different numbers of nodes and varying densities. Without normalization, comparing degree centrality across networks would be meaningless, as a high degree in one network could be low in another, depending purely on the network size. Therefore, some form of normalization or standardization is required to make meaningful comparisons. This is a simple process, with a few small tweaks made to the earlier formula.

Normalized degree centrality:²⁹

$$C_D(v) = \frac{d(v)}{\max(d)}$$

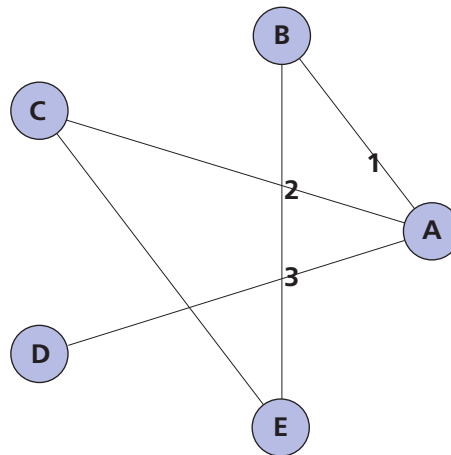
Where $\max(d)$ is local maximum degree in the graph network

This normalization scales degree centrality so that it ranges from 0 to 1. In our example, the normalized degree centrality would be 1.0 ($3 \div 3$), as 3 represents the maximum number of connections for any node in the graph (Node A has the maximum number of connections at 3, Node B has 2, Node C has 2, Node D has 1, and Node E has 2). Whereas the conventional Freeman normalization divides degree by $n - 1$, this study instead normalizes by the maximum observed degree within the network. This method enhances comparability across market samples of differing sizes and densities, acknowledging that real estate networks are typically incomplete rather than fully connected.

Interpretation:

- Nodes with high degree centrality are often considered to be important or influential,

Figure 4. Degree Centrality Count



as they have many direct connections to other nodes.

- In social networks, for example, nodes with high degree centrality represent individuals with a high level of direct interactions or influence within the network.

Closeness Centrality

Closeness centrality is defined generally as a measure of how close a node is to all other nodes in the network.³⁰ Closeness centrality assesses how quickly a property can access all other nodes in the network, reflecting overall accessibility. Properties with high closeness centrality offer efficient access to various amenities and employment centers, increasing their attractiveness.

Closeness centrality is defined as the inverse of the average shortest path distance from a node to all other nodes. The goal is to determine how efficiently information can be disseminated from one node to all others. For real estate, it can be thought of as a measure of circuitry. The basic formula is as follows:

Closeness centrality:³¹

$$C_C(v) = \frac{1}{\sum_{u \neq v} d(v, u)}$$

29. Linton C. Freeman, "Centrality in Social Networks: Conceptual Clarification," *Social Network: Critical Concepts in Sociology* 1 (2002): 238–263, <https://bit.ly/49yZrvv>.

30. Estrada, "Centrality in Networks," 405, Section 8.3.2.

31. Freeman, "Centrality in Social Networks," 238–263.

For a node v in a graph with n nodes, the normalized closeness centrality $C_C(v)$ can be expressed mathematically as:

Normalized closeness centrality:³²

$$C_C(v) = \frac{n-1}{\sum_{u \neq v} d(v,u)}$$

Where:

- n is the total number of nodes in the graph
- $d(v,u)$ is the shortest path distance between nodes v and u

The centrality value is higher for nodes that have shorter average distances to all other nodes, meaning that they are closer to the “center” of the network.

As an example, consider a simple undirected network with four nodes (A, B, C, and D). See Figure 5.

In Figure 5:

- Node A is connected to Nodes B and C.
- Node B is connected to Nodes A, C, and D.
- Node C is connected to Nodes A, B, and D.
- Node D is connected to Nodes B and C.

To calculate the closeness centrality of Node A:

1. Shortest paths:
 - A to B: distance = 1
 - A to C: distance = 1
 - A to D: distance = 2 (A→B→D or A→C→D)
2. Sum of distances: $1+1+2 = 4$
3. Calculate closeness centrality:

$$C_C(A) = \frac{4-1}{4} = \frac{3}{4} = 0.75$$

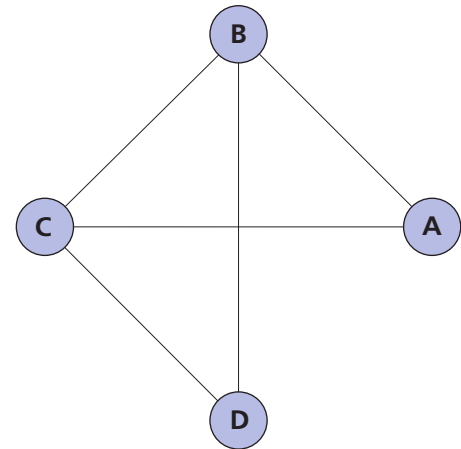
For Node B:

$$C_C(B) = \frac{4-1}{3} = \frac{3}{3} = 1.00$$

For Node C:

$$C_C(C) = \frac{4-1}{3} = \frac{3}{3} = 1.00$$

Figure 5. Undirected Network with Four Nodes



For Node D:

$$C_C(D) = \frac{4-1}{4} = \frac{3}{4} = 0.75$$

Interpretation:

- High closeness centrality: A node with high closeness centrality can reach all other nodes in fewer steps, implying that it is well-positioned to efficiently communicate with others.
- Low closeness centrality: A node with low closeness centrality is farther from other nodes, meaning it has less direct access or influence in the network.

Betweenness Centrality

Betweenness centrality assesses the extent to which a node lies on the shortest paths between other nodes, indicating its role in facilitating communication within the network.³³ For real estate, betweenness centrality identifies properties that act as critical links within the network, such as transit hubs or gateway locations (think transit stations or retail anchors). These properties may have strategic importance, making them valuable for commercial or mixed-use developments.

32. "Closeness Centrality Algorithm," *Graphable*, accessed December 5, 2024, <https://www.graphable.ai/blog/closeness-centrality-algorithm/>.

33. Estrada, "Centrality in Networks," 407, Section 8.3.3.

Betweenness centrality:³⁴

$$C_B(v) = \sum_{s \neq t \neq v} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Normalized betweenness centrality:³⁵

$$C_B^{nom}(v) = \frac{C_B(v)}{(n-1)(n-2)/2}$$

Where:

- s is the source node
- t is the target node
- $C_B(v)$ is the betweenness centrality of node v
- σ_{st} is the total number of shortest paths from node s to node t
- $\sigma_{st}(v)$ is the number of those shortest paths that pass through node v
- The summation is over all possible pairs of nodes s and t in the network ($s \neq t \neq v$)
- $(n-1)(n-2)/2$ is the maximum possible number of node pairs that could pass through node v (assuming an undirected network)

These formulas may seem complex, but by way of example the process will simplify as demonstrated for the betweenness centrality calculation for Node B. Refer to Figure 5 for a visualization of the example network. While this study focuses on degree, closeness, and betweenness centrality as accessible measures for practical implementation, future research could incorporate higher-order metrics such as Eigenvector or Katz centrality, particularly in dense or highly networked urban contexts.

Step 1: Identify All Pairs of Nodes

Our network contains Nodes A, B, C, and D. Next, consider all possible pairs of nodes, excluding pairs where B is one of the nodes (since betweenness centrality is calculated based on paths that pass through the node, not originating or ending at the node itself).

The pairs to consider are:

1. A→C
2. A→D
3. C→D

Step 2: List All Shortest Paths for Each Pair

Next, determine all the shortest paths for each pair of nodes. Below, we will specify whether Node B lies on the shortest paths between each pair.

1. A→C:
 - Shortest Path: A→C (distance = 1)
 - Does Node B lie on this path? No
2. A→D:
 - Shortest Paths: There are two possible shortest paths:
 1. A→B→D (distance = 2)
 2. A→C→D (distance = 2)
 - Does Node B lie on this path? Yes, for path A→B→D

Since there are two shortest paths between Nodes A and D, and Node B lies on one of them, the contribution of Node B for this pair is:

$$\frac{\sigma_{AD}(B)}{\sigma_{AD}} = \frac{1}{2} = 0.5$$

3. C→D:
 - Shortest Path: C→D (distance = 1)
 - Does Node B lie on this path? No

Step 3: Calculate Betweenness Centrality for Node B

Now that we have determined which paths pass through Node B, we can sum the contributions.

- A→C: Contribution = 0 (since Node B does not lie on this path)
- A→D: Contribution = 0.5 (since Node B lies on one of the two shortest paths)
- C→D: Contribution = 0 (since Node B does not lie on this path)

The betweenness centrality of Node B is the sum of all contributions:

$$C_B(v) = \sum_{s \neq t \neq v} \frac{\sigma_{st}(v)}{\sigma_{st}} = \frac{0}{0} + \frac{1}{2} + \frac{0}{0} = 0.5$$

34. "Betweenness Centrality," Wikipedia, last modified November 27, 2024, <https://bit.ly/44k2j80>.

35. "Betweenness Centrality," Wikipedia.

Finally, to normalize the betweenness centrality, the following formula can be presented:

$$\begin{aligned} C_B^{norm}(B) &= \frac{C_B(B)}{(n-1)(n-2)/2} \\ &= \frac{0.5}{(4-1)(4-2)/2} \\ &= \frac{0.5}{6/2} = \frac{0.5}{3} = 0.1667 \end{aligned}$$

Interpretation:

- Node B has a normalized betweenness centrality of 0.1667. This indicates that Node B has a moderate role in acting as a bridge in the network, connecting nodes A and D.
- The normalized value allows us to compare the centrality in a consistent range, typically between 0 and 1, regardless of the size of the network. In this case, Node B contributes significantly, but it is not a critical connector for most pairs of nodes.

Other nodes calculated:

$$\text{Node A } C_B^{norm}(A) = 0$$

$$\text{Node C } C_B^{norm}(C) = 0.1667$$

$$\text{Node D } C_B^{norm}(D) = 0$$

Centrality Summary

By calculating these centrality measures, we can create a composite network score for each property, providing a quantitative assessment of its connectivity and position within the network. This score can then be incorporated into the valuation process, adjusting property values based on their network characteristics.

Metcalfe's Law and Network Externalities

Metcalfe's Law suggests that the value of a network is proportional to the square of the number of its connected users. Applied to real estate, this implies that as more nodes (properties, amenities) are added to the network, the potential interactions increase, potentially enhancing the overall value. This principle highlights the importance of considering network externalities and the effects on a property's value caused by others within the network.

Positive network externalities occur when enhanced connectivity leads to increased economic opportunities, better access to services, and improved quality of life. For example, investments in local amenities can have spillover effects, raising nearby property values. Conversely, negative externalities, such as congestion or environmental degradation due to overconnectivity, can decrease property desirability and value.

By integrating Metcalfe's Law and network externalities into the valuation process, an exploration of the impact of these items can be undertaken to perhaps better capture the exponential impact of connectivity on property values. It should be noted, however, that the quadratic relationship implied by Metcalfe's Law is used here illustratively rather than literally; in property markets, the value effect of connectivity likely follows a nonlinear but sub-quadratic pattern, reflecting diminishing marginal utility as networks mature.

Benefits of the Network Valuation Approach

The network valuation approach (NVA) offers several significant benefits over traditional methods. First of all, it could provide a more holistic valuation by providing a comprehensive assessment that incorporates both tangible and intrinsic factors that are recognized or increasingly perceived by market participants, including social capital, community engagement, and economic synergy. This approach aligns with contemporary buyer and tenant priorities, such as sustainability, connectivity, and community well-being. The method reflects dynamic changes in the network over time, such as new infrastructure developments or shifts in social dynamics, providing a more responsive and future-oriented valuation. It enables the forecasting of future property values by modeling potential network developments. It could also assist in the identification of "hidden value," wherein properties that may seem undervalued through traditional methods might demonstrate potential worth when their network position is considered and as market participants begin to recognize those connections. This insight aids investors and policymakers in making informed decisions, guiding investments toward opportunities where network effects can amplify returns.

Readers may recall the value premise called *public interest value*. *The Appraisal of Real Estate* has this to say about public interest value:

Historically, *public interest value* has been used as a general term covering a family of value concepts that relate the highest and best use of property to noneconomic uses. (Other terms for similar concepts include *aesthetic value*, *scenic value*, *preservation value*, and *social value*.) The analysis of public interest value tends to be driven by social, political, and public policy goals rather than economic principles.³⁶

The distinction here is that an NVA is based on economic principles capturing both the tangible and intrinsic benefits that accrue.

Developing a Network Valuation Approach

The challenge now is moving from theory and data (the various centrality measures) to a practical valuation model. Essentially, an appraiser would need a functional relationship that maps network metrics to dollar values. Unlike simple per-square-foot measures, this involves developing a new kind of valuation formula that *empirically connects centrality to price*. There are several structured approaches that could be attempted, which are discussed below.

Approach 1: Calibrate a Hedonic Regression or Econometric Model

To make network measures a “stand-alone” tool, start by treating them as independent variables in a pricing model and then statistically derive their contribution to value.

Steps

The steps to calibrate a hedonic regression or econometric model are as follows:

- **Data collection:** Gather a large dataset of properties with known sale prices or values. Include attributes such as size, building quality, property rights conveyed, and so

forth, but focus on also having the network-based metrics for each property’s location (e.g. direct, closeness, betweenness centrality).

- **Model specification:** Start with a hedonic regression model: $\ln(\text{Price}) = \alpha + \beta_1(\text{Degree Centrality}) + \beta_2(\text{Closeness Centrality}) + \beta_3(\text{Betweenness Centrality}) + \dots$ where α is the intercept or the baseline level of the natural logarithm of the property price when all explanatory variables are equal to zero.

Even if the aim is for a stand-alone, network-based approach, initially including conventional controls (physical characteristic dummies, structural attributes, etc.) could be helpful for model calibration. Later, an appraiser can progressively reduce non-network variables if the goal is a purely network-driven model.

- **Derive coefficients:** Once the regression model is run, the coefficients ($\beta_1, \beta_2, \beta_3$) will tell the relationship between each centrality measure and price. If the model is well-fitted, one can theoretically estimate a property’s value based solely on its network characteristics.

Outcome

This gives an appraiser a predictive equation. For a subject property, an appraiser would calculate its centralities and plug them into the regression equation to get an estimated value. The benefit of this model is that other attributes, elements of comparison, or features could be considered as part of the regression model. This is likely a practical approach to the modeling question and will be demonstrated with a case study.

Approach 2: Use Machine Learning for Functional Approximation

If linear or log-linear forms aren’t adequate, an appraiser could consider more flexible methods.

Steps

The steps for using machine learning for functional approximation are as follows:

36. *The Appraisal of Real Estate*, 15th ed., 54.

- Machine learning models: Train a model on historical sales data along with the network metrics.³⁷
- Feature importance: Determine which centrality measures best predict price.
- Predictive tool: Once trained, this model could estimate value for any property by simply feeding in the network metrics (and minimal other information if desired).

Outcome

The outcome is more likely an opaque model that directly maps network measures to a price/value prediction. Under USPAP Standards Rule 1-4(g), appraisers must analyze relevant agreements and understand the methods and techniques used in the valuation. The “black box” nature of complex machine learning models may make it difficult to satisfy USPAP’s requirements for transparency, credibility of assignment results, and the appraiser’s ability to explain and defend the methodology. An appraiser relying on such models would need to clearly communicate both the model’s logic and its limitations to meet professional standards.

Approach 3: Use Centrality as a Benchmark and Derive Multipliers

Instead of developing the entire valuation from scratch, an appraiser could consider using network measures to derive multipliers or indexes that adjust a baseline value estimate.

Steps

The steps to use centrality as a benchmark and derive multipliers are as follows:

- Start with a baseline value for a given property type (such as replacement cost, appraised value, or sale price).
- Derive a “network value index” (NVI) from the centrality metrics. For example, transform each centrality measure into a normalized score (0 to 1), then combine them into a single NVI for a property (P).

$$\begin{aligned} NVI(P) &= w_1 \times \frac{Degree(P)}{\max(Direct)} \\ &\times w_2 \frac{Closeness(P)}{\max(Closeness)} \\ &\times w_3 \frac{Betweenness(P)}{\max(Betweenness)} + \dots \end{aligned}$$

- Calibrate a multiplier from historical data:

$$Value(P) = Base\ Value \times f(NVI(P))$$

where f could be a linear or nonlinear function derived from a regression that links NVI to observed market values

Outcome

This approach provides a valuation model grounded in network theory but expressed as a predictive formula or algorithm that can be applied to known values. Using this technique, appraisers could determine an NVI for several sales and see what premiums may exist for better-connected properties.

Developing a Practical Network Valuation Model

The following section outlines a potential framework for translating the theoretical concepts of network theory into a practical valuation model, starting with an NVI and then developing a hedonic regression model using the NVI as a critical input. As noted, this approach has the ability to expand to other elements of comparison or features and can be made as complex as necessary to address the valuation problem. While some traditional adjustments involve professional judgment, this interpretive element reflects the appraiser’s role in modeling market perception rather than opinion.

37. These models would use tools like random forests, which are ensemble learning methods that combine multiple decision trees to improve prediction accuracy and reduce overfitting. Other model engines could include gradient boosting machines that build models sequentially, with each new model correcting errors from previous ones, resulting in highly accurate but complex predictions. Finally, neural networks could be used and are computational models inspired by biological neurons that learn patterns through interconnected layers of nodes, capable of capturing highly nonlinear relationships in data.

Defining Centrality Measures in a Real Estate Context

To put the centrality measures discussed earlier into practical use, we need to define their application specifically within the context of real estate markets.

Degree Centrality (Direct Connections)

For our purposes, degree centrality measures the number of direct connections a property has to key amenities and services within a defined radius. These connections could include:

- **Accessibility:** The number of major roads, highways, or public transit stops within a defined radius or polygon (weighted by type and capacity)
- **Amenities:** The number of schools, parks, hospitals, grocery stores, restaurants, etc. within a defined radius or polygon (weighted by type and quality rating, if available)
- **Employment:** The number of major employers (defined by employee count) within a defined radius or polygon
- **Digital connectivity:** The presence of high-speed internet service providers and cell towers within a defined radius or polygon

Data Sources

This information can be gathered from GIS databases, government planning departments, real estate data providers like CoStar or Yardi Matrix, and web scraping tools to extract data from OpenStreetMap, Google Maps, Yelp, or similar platforms.

Closeness Centrality (Overall Accessibility)

Closeness centrality quantifies how easily a property can access all other nodes (amenities, services, employment centers) within the defined network. This could be calculated using:

- **Travel time:** Average travel time (by car and public transit) to all other nodes in the network, weighted by the importance of each node
- **Distance:** Average distance to all other nodes, weighted by the importance of each node

Data Sources

Travel time data can be obtained from application programming interfaces (APIs) like Google Maps

Distance Matrix API or even more basic self-developed measures by looking at mapping programs that can estimate travel time. Distance can be calculated using GIS software or other software tools.

Betweenness Centrality (Critical Linkage)

Betweenness centrality identifies properties that serve as important connectors within the network. This could include:

- **Intersection properties:** Properties located at major intersections or along heavily trafficked corridors
- **Transit-oriented developments:** Properties that bridge residential and commercial areas or connect different transit lines
- **Mixed-use properties:** Properties that combine residential, commercial, and/or recreational uses, acting as hubs within their immediate surroundings

The relevance of these linkages ultimately depends on how market participants perceive and respond to them, but network analysis provides a structured way to observe and measure the kinds of spatial and functional relationships that may contribute to perceived value.

Data Sources

GIS data, planning documents, and real estate databases can be used to identify these types of properties.

Creating a Standardized Network Value Index

To create a user-friendly metric, combine the weighted and normalized centrality measures into a single network value index (NVI) for each property. The steps for this process are as follows:

1. **Normalization:** Each centrality measure will be normalized to a 0-1 scale, where 1 represents the highest centrality within the data set.
2. **Weighting:** Each centrality measure will be assigned a weight reflecting its relative importance to property value. These weights can be determined through expert opinion, surveys of real estate professionals, or statistical analysis. For initial development, the following weights are proposed:

- Degree centrality: 40%
- Closeness centrality: 40%
- Betweenness centrality: 20%

These initial ratios reflect an assumed balance between local accessibility (degree and closeness) and broader network intermediation (betweenness). They are not presented as universal or definitive but as pragmatic starting parameters that align with observed appraisal logic emphasizing proximity and access. In practice, future implementations should test the robustness of results through sensitivity analysis or expert weighting exercises to ensure context-specific validity as noted earlier in this article.

3. **Formula:** The NVI will be calculated as follows:

$$\text{NVI} = (0.4 * \text{Normalized Degree Centrality}) + (0.4 * \text{Normalized Closeness Centrality}) + (0.2 * \text{Normalized Betweenness Centrality})$$

To demonstrate the efficacy of the NVI, a large dataset of property transactions could be assembled, including sale prices, property characteristics, and the calculated centrality measures for each property. For this article, a starting point has been set based on the suggested ratios. In practice, this would need refinement.

The weighting of nodes, distances, and connections within the NVI model can be tailored to reflect differing buyer and seller preferences across market segments. For example, younger first-time buyers may assign greater value to proximity to schools and employment centers, while older households may prioritize healthcare access and social infrastructure. As market behavior evolves, the model's calibration should likewise adapt to new patterns of preference and perception.

Model Specifications

Once the NVIs have been calculated, a hedonic regression model could be used to estimate the relationship between property value and the NVI, controlling for other relevant factors. This allows for a determination of the statistical significance of the NVI and a quantification of its impact on value. The model will take the following form:

$$\ln(\text{Price}) = \alpha + \beta_1(\text{NVI}) + \beta_2(\text{Property Characteristics}) + \beta_3(\text{Property Rights}) + \epsilon$$

Where:

- $\ln(\text{Price})$ is the natural logarithm of the sale price
- NVI is the network value index
- Property Characteristics is a vector of property-specific attributes (e.g., size, age, condition)
- Property Rights Conveyed is a vector of the property rights conveyed (e.g., leased fee, fee simple, or leasehold)
- ϵ is the error term

The use of the natural logarithm of price, $\ln(\text{Price})$, in the hedonic regression model is a common practice in real estate valuation and econometrics for several important reasons.³⁸ The relationship between property value and its attributes (including network attributes) is often nonlinear. For example, the increase in value from adding an extra bedroom might be smaller for a large house than for a small one. Using the logarithm of price helps to capture these diminishing marginal returns, as the logarithmic function grows at a decreasing rate.

Taking the logarithm allows for an interpretation of the coefficients of the independent variables as approximate percentage changes in price. For example, if the coefficient of NVI is 0.05, it suggests that a 1-unit increase in NVI is associated with an approximate 5% increase in property value. This interpretation is often more intuitive and meaningful than interpreting the coefficients in terms of absolute changes in price.

38. For a comprehensive discussion of the theoretical and empirical rationale for log-price specifications in hedonic models, see Stephen Malpezzi, "Hedonic Pricing Models: A Selective and Applied Review," in *Housing Economics and Public Policy: Essays in Honor of Duncan MacLennan*, ed. Tony O'Sullivan and Kenneth Gibb (Blackwell Science, 2003), 67–89.

Another reason to use the logarithm of the price transformation is that property prices often exhibit positive skewness, meaning they have a long right tail with a few very expensive properties. This can violate the normality assumption of linear regression, potentially leading to biased and inefficient estimates. Taking the logarithm of price often reduces this skewness, making the distribution of the dependent variable closer to a normal distribution.

In addition, heteroscedasticity occurs when the variance of the error term in the regression model is not constant across different levels of the independent variables. This can also violate the assumptions of linear regression and affect the validity of statistical inference. Using the logarithm of price can help to stabilize the variance of the error term and reduce heteroscedasticity.

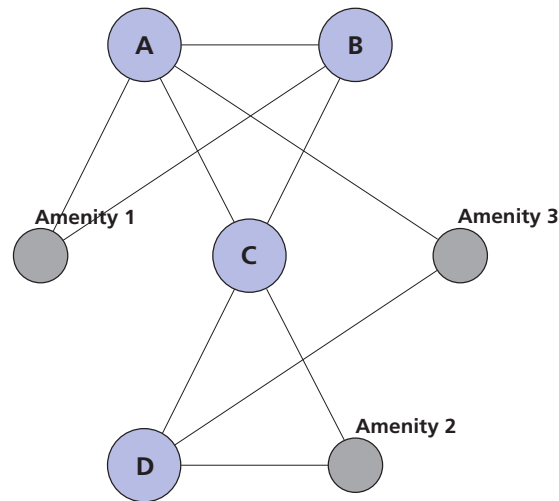
There are several approaches to developing a model under this construct. Depending on data availability and the skill set of the valuer, machine learning algorithms such as random forests or gradient boosting could be employed to explore non-linear relationships between the NVI and property value and potentially improve predictive accuracy. For these initial purposes, a simpler approach will be followed to demonstrate conceptually how a model like this could be implemented.

Illustrative Case Study

To demonstrate the practical application of the network valuation approach (NVA), consider a hypothetical neighborhood comprising four properties (labeled A through D). This is an illustrative case and is not meant to convey empirical validation. Each property's proximity to three key amenities is analyzed to calculate a simplified network value index (NVI). This index serves as a proxy for network connectivity, which is then examined for its relationship to property sale prices using a basic hedonic regression model.

This example is simplified for illustrative purposes. In a real-world scenario, there would likely be many properties, more network attributes or amenities, and potentially more sophisticated centrality measures. There are readily available tools for much of this analysis, including GIS software and open-source programming packages to do most of the difficult calculations. Traditional spreadsheet packages can also be used. This example has been stripped down to just a few properties and nodes to

Figure 6. Property and Amenity Network



aid in understanding, but this approach can certainly be applied to a more robust dataset and valuation scenario. Figure 6 represents the property and amenity network for this case study.

Data Overview

The network for this case study includes the following attributes as illustrated in Figure 6. The properties are labeled as Nodes A, B, C, and D, with the network also including some amenities simply named Amenity 1, Amenity 2, and Amenity 3. These amenities could be things such as proximity to a transit center, nearby schools, recreational facilities, or any other node that could have an impact on the overall value of the property, depending on the property type. For this discussion, the property types and network attributes or amenities have purposefully been labeled in a generic fashion. The following lists outline the various connections shown in the network and amenity image in Figure 6.

The property-to-property connections are as follows:

- A is connected to B.
- A is connected to C.
- B is connected to C.
- C is connected to D.

The property-to-amenity connections are as follows:

- A is connected to Amenity 1.
- A is connected to Amenity 3.
- B is connected to Amenity 1.

Table 1. Direct Centrality Adjacency Matrix

Node	A	B	C	D	Amenity 1	Amenity 2	Amenity 3
A	0	1	1	0	1	0	1
B	1	0	1	0	1	0	0
C	1	1	0	1	0	1	0
D	0	0	1	0	0	1	1
Amenity 1	1	1	0	0	0	0	0
Amenity 2	0	0	1	1	0	0	0
Amenity 3	1	0	0	1	0	0	0

- C is connected to Amenity 2.
- D is connected to Amenity 2.
- D is connected to Amenity 3.

Methodology: Quantifying Network Connectivity

The NVA relies on centrality metrics to quantify network connectivity. Prior sections of the article detailed those measures and the appropriate method to determine the normalized calculations. This simplified model will use the measures summarized below:

- Degree centrality: For the purposes of this case study, degree centrality quantifies the number of direct connections a property has with key nodes such as the amenities shown in the network graph (see Figure 6). Properties with higher degree centrality are often more desirable due to increased convenience and accessibility.
- Closeness centrality: Closeness centrality assesses how quickly a property can access all other nodes in the network, reflecting overall accessibility. Properties with high closeness centrality offer efficient access to various amenities and employment centers, increasing their attractiveness.
- Betweenness centrality: Betweenness centrality assesses the extent to which a node lies on the shortest paths between other nodes. Betweenness centrality identifies properties that act as critical links within the network, such as transit hubs or gateway locations. These properties may have strategic importance.

Direct Centrality Adjacency Matrix

The direct centrality adjacency matrix shown in Table 1 expands the analysis by incorporating both properties and amenities. An adjacency matrix is a table used to illustrate the connections between nodes in a network. Each row and column correspond to a specific node, such as a property or amenity. The entries in the matrix indicate whether a direct relationship exists between the nodes, with 1 signifying a connection between a property and an amenity or another property, and 0 indicating no direct connection. This matrix is symmetrical, meaning that the connection from Node A to B is the same as the connection from Node B to A, which is appropriate for an undirected network of properties and amenities. This is a simple way to calculate the direct centrality and transpose the network graph in Figure 6 from a visualization to a number-based matrix.

Two interesting patterns emerge from the direct centrality adjacency matrix:

- The matrix reveals important insights about how properties are physically connected and how users can access various amenities within the development.
- Regarding property connectivity and access, Property C emerges as a key connecting point in the development, offering direct pathways to three other properties (A, B, and D) and access to one amenity (Amenity 2). This suggests Property C likely sits at a crucial intersection of walkways, streets, or paths that facilitate resident movement throughout the community. Properties A

Table 2. Closeness Centrality Adjacency Matrix

Node	A	B	C	D	Amenity 1	Amenity 2	Amenity 3
A	0	1	1	2	1	2	1
B	1	0	1	2	1	2	2
C	1	1	0	1	2	1	2
D	2	2	1	0	3	1	1
Amenity 1	1	1	2	3	0	3	2
Amenity 2	2	2	1	1	3	0	2
Amenity 3	1	2	2	1	2	2	0

and B appear to be in a well-established section of the development, with good internal connectivity and shared access to Amenity 1. Property A has the added advantage of access to Amenity 3, potentially making it more attractive to potential users who value multiple amenity options within easy reach. Property D, while having fewer direct property connections, offers users direct access to two amenities (Amenities 2 and 3). This could be particularly appealing to those who prioritize amenity access over internal community connections, perhaps representing a quieter section of the development with good amenity proximity.

This pattern of connections suggests a network where no property is isolated and amenities are distributed in a way that ensures reasonable access across the development, with some properties serving as key connection points for both other properties and amenities.

Closeness Centrality Adjacency Matrix

The closeness centrality adjacency matrix shown in Table 2 outlines the shortest path distances between all pairs of nodes in the network, effectively measuring how many steps it takes to get from any one location (property or amenity) to another through the existing connections. A distance of 1 indicates directly connected nodes, while higher numbers indicate nodes that require traveling through intermediary locations to reach each other.

Several interesting observations emerge from this matrix:

- Regarding property interconnections, Properties A, B, and C form a tightly connected cluster, with direct connections between them (distance = 1). Property D is slightly more peripheral, requiring two steps to reach Properties A and B, though it maintains a direct connection to Property C.
- Regarding amenity accessibility, Amenity 1 is particularly well-positioned, having direct connections to both Properties A and B. This suggests it's a highly accessible facility within the network. Properties C and D share access to Amenity 2, creating a shared resource point in the network structure. Amenity 3 shows a distinctive pattern, being directly accessible from Properties A and D but requiring additional steps to reach from Properties B and C. This creates an interesting "bookend" effect, where the amenity is accessible from opposite ends of the property chain. Finally, the maximum distance in the network is three steps, indicating a relatively compact and efficient network structure where no point is too isolated from any other. This suggests good overall connectivity and accessibility throughout the system.

Betweenness Centrality Pathways

As outlined earlier, the betweenness centrality is a measure of the shortest path between each pair of nodes. For a shortest path to exist and for a node to have betweenness centrality, it must lie on at least one shortest path between two other nodes. Betweenness centrality is context-sensitive, meaning that nodes that appear structurally similar may not contribute equally to the shortest

paths, depending on their network connections.

An adjacency matrix may not best illustrate this concept, so Table 3 has been provided to show the shortest paths for the betweenness centrality measures.

Centrality Measures (Calculations)

The summary of the raw and normalized centrality measures is shown in Table 4, following those formulas and explanations provided earlier in this article.

The analysis of normalized centrality measures within this property development network reveals insights into how the properties and amenities interact and function as an integrated community. The network structure demonstrates how properties connect both to each other and to various amenities, creating a complex web of accessibility and interaction opportunities.

Looking first at direct connectivity through degree centrality, Properties A and C emerge as the most well-connected locations within the development, with each achieving maximum normalized degree centrality scores. These properties benefit from optimal positioning that provides immediate access to both neighboring properties and community amenities. Property A's connections link it directly to two other properties while also providing immediate access to two amenities, creating an enviable position for users or investors seeking balanced access to both community interaction and amenity usage. Property C mirrors this level of connectivity but with a different configuration, connecting to three other properties and one amenity, suggesting it might serve as more of a community hub within the property network.

Properties B and D demonstrate strong, though not optimal, connectivity within the network. Their positions offer users and investors multiple pathways for accessing both neighbors and amenities, maintaining three strategic connections each. This level of connectivity suggests these properties, while not central hubs, still provide substantial flexibility in how they move through and engage with the community.

When examining the strategic positioning through closeness centrality, a similar but more nuanced picture emerges. Properties A and C again lead in this measure, indicating they offer users and investors the most efficient access to all other locations within the development. The high closeness centrality suggests that users and investors of these properties would experience

minimal travel distances whether accessing amenities or visiting neighbors. Property B follows closely behind, suggesting only marginally longer average paths to reach all destinations, while Property D shows lower but still significant accessibility, reflecting its more peripheral position in the property network.

The betweenness centrality analysis reveals particularly interesting insights about how movement flows through the property network. Property C emerges as a crucial connector, suggesting it serves as a critical pathway for movement throughout the community. This position might make it particularly valuable for residents who prioritize being in the heart of community activity. Property A also shows significant importance as a transit point, though slightly less than Property C. Properties B and D appear to function more as destination points rather than thoroughfares, which might appeal to users and investors seeking slightly more privacy while still maintaining good community access.

The amenities themselves show careful integration into the property network's fabric. While all amenities maintain consistent direct connectivity, Amenity 3 demonstrates higher accessibility and plays a minor role in network flow, suggesting it might serve as both a destination and a convenient pass-through point for users and investors. Amenities 1 and 2 function purely as destination points, indicating they might be designed more for dedicated use rather than casual interaction.

This property network structure suggests a development carefully planned to balance community interaction with amenity access. The positioning of Properties A and C as premium locations offers optimal connectivity and accessibility. Properties B and D maintain balanced access while potentially offering more privacy. No property is more than two links from any amenity, ensuring reasonable access for all residents, while the varying levels of centrality create natural neighborhoods within the development that might appeal to different users' and investors' preferences and lifestyles.

Network Value Index

As noted previously, a network value index (NVI) needs to be calculated prior to running a regression model. This metric represents a measure for how "well-connected" the property is considering the various measures of centrality as summarized in Table 4. The NVI is then calculated as

Table 3. Betweenness Centrality Measures

Node A		
Source → Target	All Shortest Paths	Through A
B → D	B→C→D, B→A→C→D	1/2
B → Amenity 2	B→C→Amenity 2, B→A→C→Amenity 2	1/2
B → Amenity 3	B→A→Amenity 3, B→C→D→Amenity 3, B→A→C→D→Amenity 3	2/3
C → Amenity 3	C→D→Amenity 3, C→A→Amenity 3	1/2
D → Amenity 1	D→C→B→Amenity 1, D→C→A→Amenity 1	1/2
Amenity 1 → Amenity 2	Amenity 1→B→C→Amenity 2, Amenity 1→A→C→Amenity 2	1/2
Amenity 1 → Amenity 3	Amenity 1→A→Amenity 3	1/1
Node B		
Source → Target	All Shortest Paths	Through B
A → Amenity 1	A→Amenity 1, A→B→Amenity 1	1/2
C → Amenity 1	C→A→Amenity 1, C→B→Amenity 1	1/2
D → Amenity 1	D→C→A→Amenity 1, D→C→B→Amenity 1	1/3
Node C		
Source → Target	All Shortest Paths	Through C
A → D	A→C→D	1/1
A → Amenity 2	A→C→Amenity 2	1/1
B → D	B→C→D, B→A→C→D	2/2
B → Amenity 2	B→C→Amenity 2, B→A→C→Amenity 2	2/2
Amenity 1 → D	Amenity 1→A→C→D, Amenity 1→B→C→D	2/2
Amenity 1 → Amenity 2	Amenity 1→A→C→Amenity 2, Amenity 1→B→C→Amenity 2	2/2
Node D		
Source → Target	All Shortest Paths	Through D
A → Amenity 2	A→C→Amenity 2, A→C→D→Amenity 2	1/2
B → Amenity 2	B→C→Amenity 2, B→C→D→Amenity 2	1/2
C → Amenity 3	C→D→Amenity 3, C→A→Amenity 3	1/2
Amenity 3		
Source → Target	All Shortest Paths	Through Amenity 3
A → D	A→C→D, A→Amenity 3→D	1/2
Amenity 1 → D	Amenity 1→A→C→D, Amenity 1→A→Amenity 3→D	1/3

Note: Amenity 1 and Amenity 2 do not serve as network bridges as they are isolated features that connect to nearby properties but do not link different parts of the property network together. Therefore they have a 0 betweenness centrality measure and are not shown in Table 3.

Table 4. Summary of Raw and Normalized Centrality Measures

	Property and Amenity Network					
	Degree Centrality		Closeness Centrality		Betweenness Centrality	
	Total Degree	Normalized Degree	Raw Closeness	Normalized Closeness	Raw Betweenness	Normalized Betweenness
A	4	1.000	0.125	0.750	4.167	0.278
B	3	0.750	0.111	0.667	1.333	0.089
C	4	1.000	0.125	0.750	5.167	0.344
D	3	0.750	0.100	0.600	1.500	0.100
Amenity 1	2	0.500	0.083	0.500	0.000	0.000
Amenity 2	2	0.500	0.091	0.545	0.000	0.000
Amenity 3	2	0.500	0.100	0.600	0.833	0.056

a weighted average of the normalized centrality measures. The following weights: Degree Centrality (40%), Closeness Centrality (40%), and Betweenness Centrality (20%) applied to this formula:

$$\begin{aligned} \text{NVI} = & 0.4 \times \text{Degree Centrality} \\ & + 0.4 \times \text{Closeness Centrality} \\ & + 0.2 \times \text{Betweenness Centrality} \end{aligned}$$

Table 5 outlines these measures applied to the sample data set. In addition, the sale prices have been shown along with the natural log of the sale price for use in the regression model that follows.

Regression Analysis

To assess the impact of network connectivity on property values, a simple linear regression model can be employed as follows:

$$\ln(\text{Network Value}) = \alpha + b(\text{NVI})$$

The coefficient α represents the intercept of the regression model and is the expected value of $\ln(\text{Network Value})$, the natural logarithm of the estimated network value, when $\text{NVI} = 0$. The coefficient b represents the relationship between the NVI and the natural log of sale price, offering insights into the significance of network connectivity.

The regression statistics as shown in Table 6 were calculated using Microsoft Excel.

The following is a breakdown of the key statistics and what they indicate.

- Regression statistics:
 - Multiple R (0.9110): This is the correlation coefficient between the NVI and the natural log of the Sale Price. It's very close to 1, indicating a strong positive linear relationship.
 - R Square (0.8300): This is the coefficient of determination. It tells us that approximately 83.0% of the variation in the natural log of Sale Price is explained by the NVI. This is a high R-squared, suggesting the NVI is a strong predictor of sale price in this specific sample.
 - Adjusted R Square (0.7450): This is similar to R Square but adjusts for the number of predictors in the model. It is slightly lower than R square, which is normal. It still indicates a good fit, but keep in mind that this is small dataset.
 - Standard Error (0.0533): This measures the average distance that the observed values fall from the regression line. A smaller standard error is better, and this is relatively small, suggesting good precision in the model.
 - Observations (4): This confirms the number of data points used in the regression.

Table 5. Network Value Index (NVI) and Sale Prices

	Centrality Measures Normalized			NVI	Sale Price	ln(Sale Price)
	Degree	Closeness	Betweenness			
A	1.000	0.750	0.278	0.756	\$300,000	12.612
B	0.750	0.667	0.089	0.584	\$280,000	12.543
C	1.000	0.750	0.344	0.769	\$320,000	12.676
D	0.750	0.600	0.100	0.560	\$250,000	12.429

Table 6. Regression Statistics

Regression Statistics	
Multiple R	0.9110
R Square	0.8300
Adjusted R Square	0.7450
Standard Error	0.0533
Observations	4

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1.000	0.028	0.0 28	9.765	0.089
Residual	2.000	0.006	0.003		
Total	3.000	0.033			

	Coefficients	Standard Error	t-stat	p-value	Lower 95%	Upper 95%
Intercept	11.983	0.188	63.658	0.000	11.173	12.792
NVI	0.873	0.279	3.125	0.089	-0.329	2.074

- ANOVA—overall significance of the regression model:
 - Significance F (0.089): This is the p -value for the F -test, indicating whether the overall regression model is statistically significant. With a value of 0.089, it is greater than 0.05, meaning the model is not statistically significant at the 5% level but could be considered significant at the 10% level. Again, in this case we are dealing with a very small data set for ease of understanding.
- Coefficients
 - Intercept (11.983): The estimated value of $\ln(\text{Sale Price})$ when $\text{NVI} = 0$. The p -value for the intercept is extremely small (<0.0001), indicating the intercept is highly significant.
 - NVI (0.4380): This is the slope coefficient, indicating that for every 1-unit increase in NVI, the natural log of the sale price ($\ln(\text{Sale Price})$) increases by 0.873, on average. The p -value for NVI is 0.089, which suggests that the relationship between NVI and $\ln(\text{Sale Price})$ is not statistically significant at the 5% level but may be significant at the 10% level.
 - Standard error (for the coefficients): These values measure the precision of your estimated coefficients. Smaller standard errors are better. Your standard errors are relatively small, suggesting good precision. The statistical significance observed at approximately the 10% level should be interpreted considering the study's limited sample size of only four observations. With such a small number of data points, even moderate relationships can yield relatively weak p -values due to constrained degrees of freedom. The results are therefore best viewed as illustrative of the NVA's conceptual and computational feasibility rather than as evidence of robust predictive accuracy. In future research, the use of larger datasets and the inclusion of confidence intervals for predicted values will allow for a more rigorous assessment of model performance.
 - t -statistic: Used to calculate the p -values.
 - Lower 95% and Upper 95%: These are the lower and upper bounds of the 95% confidence interval for your NVI coefficient.

cient. They give you a range within which the *true* population coefficient is likely to fall. It is best if it does not include 0.

Interpretation

Under this very simple case study dataset, the mechanics of the process have been outlined. To apply this to a subject property, let's assume we have followed a similar process and determined the subject property had an NVI of 0.784. The model would predict its value as follows:

$$\begin{aligned} \ln(\text{Network Value}) &= \alpha + b(\text{NVI}) \\ \ln(\text{Subject}) &= 11.983 + 0.873(0.784) \\ \ln(\text{Subject}) &= 11.983 + 0.684 \\ \ln(\text{Subject}) &= 12.667 \\ \text{Subject} &= \$317,246 \\ \text{Subject} &= \$317,000 \text{ (rounded)} \end{aligned}$$

Furthering the conversation around this approach and interpreting results through a review of additional scenarios amplifies these findings.

Scenario 1: Traditional Appraisal = \$300,000, NVI-Based Value = \$317,000

In this case, the NVI-based value estimate (\$317,000) is higher than the traditional appraisal of \$300,000. This suggests that the traditional approaches (cost, sales comparison, and income capitalization) might be *undervaluing* the property by not fully capturing the positive impact of its network connections.

Possible explanations could include that the property's location within the network might offer intrinsic benefits that traditional methods don't adequately quantify. For example, it might be closer to desirable amenities, have better access to transportation, or be part of a stronger social network, all of which contribute to its value but are difficult to measure using standard appraisal techniques. Also, the market might be placing a premium on network connectivity that traditional appraisals, which often rely on historical data, haven't fully caught up with. The NVI, if calibrated correctly, might be a leading indicator of value in this case. In addition, there could be differences in the data used for the traditional appraisal versus the NVI calculation. The NVI might be incorporating more up-to-date or granular data on network attributes.

This scenario suggests that relying solely on traditional methods might undervalue properties with strong network connections, potentially

leading to missed opportunities for sellers and inaccurate assessments for buyers.

Scenario 2: Traditional Appraisal = \$350,000, NVI-Based Value = \$317,000

Here, the traditional appraisal of \$350,000 is significantly higher than the NVI-based estimate of \$317,000. This indicates that the traditional methods might be *overvaluing* the property relative to what its network connectivity suggests.

Possible explanations could be that the traditional appraisal might be placing too much weight on the property's physical attributes (e.g., size, condition, finishes) while not adequately considering its relatively weaker network position. Also, the market might be experiencing a speculative bubble in the area, driving up prices beyond what the underlying fundamentals, including network value, would justify. Finally, the property might possess unique characteristics not captured by either the traditional methods or the NVI model. These could be factors like historical significance, architectural distinctiveness, or a particularly desirable view that command a premium.

This scenario highlights the potential for the NVI to serve as a check on traditional appraisals, particularly in markets where prices might be inflated or where physical characteristics are overemphasized. It suggests that relying solely on traditional methods in such cases could lead to overvaluation.

Summary of Case Study

This example demonstrates the basic mechanics of the network valuation approach (NVA). By quantifying network connectivity and incorporating it into a valuation model, we can potentially gain a more comprehensive understanding of property value. Further development and refinement of this approach using real-world data and more sophisticated techniques could lead to a valuable tool for appraisers, investors, and urban planners.

In essence, the NVA provides an additional lens through which to view property value. By comparing its results with traditional appraisals, appraisers can gain a more nuanced understanding of a property's worth and potentially identify situations where one approach might be overestimating or underestimating value.

Addressing Potential Challenges and Limitations

While the NVA offers a promising avenue for enhancing real estate valuation, it is essential to acknowledge and address potential challenges and limitations. The case study was developed with ease in mind. No doubt other elements of comparison would likely need to be included in any robust regression model to account for other differences in the properties.

The accuracy and reliability of the NVI are contingent upon the availability and quality of underlying data. In some areas, particularly in less developed or data-scarce regions, obtaining comprehensive and up-to-date information on network connections, amenities, and other relevant factors may be challenging. Appraisers may need to rely on a combination of data sources, including publicly available data, commercial databases, and potentially even field surveys, to fill in data gaps. Furthermore, data quality can vary across sources, requiring careful vetting and potentially limiting the precision of the NVI in certain cases. Future development of the model will need to address how best to handle missing or unreliable data, potentially through imputation techniques or sensitivity analysis.

Despite the quantitative nature of the NVI, some degree of subjectivity is inherent in defining what constitutes a "direct connection" or a "critical link" and in assigning weights to different network components. For instance, the radius used to define proximity to amenities or the criteria for identifying a "major employer" may require judgment calls. To mitigate this, clear guidelines and standardized criteria should be developed, and the rationale for weighting choices should be transparently documented. Furthermore, the model should be tested with different weighting schemes to assess the sensitivity of the NVI to these choices. Future iterations could allow for user-defined inputs for some of these parameters, allowing appraisers to tailor the model to specific market conditions.

Cities are constantly evolving with new infrastructure projects, changing demographics, and shifting social patterns. The NVI, as a snapshot of network connectivity at a given point in time, needs to be regularly updated to reflect these

changes. This requires ongoing monitoring of network developments and periodic recalibration of the model. Appraisers will need access to updated data and tools to ensure their valuations reflect the current state of the network. Future research could explore the feasibility of incorporating dynamic network data to enhance the model's responsiveness to change.

Calculating the NVI, particularly the closeness and betweenness centrality measures, can be computationally intensive for large networks. Although some elements of network computation may appear technical, the underlying workflows can be implemented using standard, freely available software. Publicly accessible data from sources such as OpenStreetMap, U.S. Census TIGER/Line files, and municipal GIS portals can serve as inputs. Appraisers can calculate the core network metrics of degree, closeness, and betweenness centrality through open-source platforms like QGIS or statistical environments such as R (using the *sf* and *igraph* packages) or Python (*networkx*). These tools automate the necessary computations with minimal coding, allowing practitioners to incorporate the NVI without specialized technical infrastructure.

Conclusion

The integration of network theory into real estate valuation offers a transformative perspective that aligns with the complexities of modern urban environments. By recognizing properties as interconnected nodes within broader networks, we can capture the added value generated through their relationships and connectivity. This approach addresses the limitations of traditional methods by incorporating the dynamic and synergistic aspects of real estate, ultimately leading to more accurate and insightful valuations.

The network valuation approach (NVA) not only enhances the accuracy of property valuations but also has the potential to positively influence urban development. It encourages investments that enhance connectivity and community integration, informs urban planning and infrastructure investment decisions, and provides investors with deeper insights into property value drivers.

By adopting this approach, the real estate industry can unlock new dimensions of value, fostering developments that contribute positively to the fabric of society. This approach reflects a more accurate understanding of how properties function within the complex networks that define modern life, paving the way for innovative solutions and sustainable growth.

Further research is needed to refine the NVA, including developing standardized methodologies, creating accessible analytical tools, and conducting empirical studies to validate the approach. Collaboration among academics, industry professionals, and others will be essential to advance this field and realize its full potential.

By integrating network theory into real estate valuation, new avenues open for credibly developing property values in a manner that reflects the complexities of modern life. The NVA provides a robust and defensible framework suitable for professional practice and academic inquiry, offering a significant contribution to the field of real estate valuation.

The NVA represents a paradigm shift in real estate appraisal by systematically incorporating the value of connectivity and synergy. This approach aligns with evolving market dynamics when buyers and investors increasingly value properties not just as stand-alone assets but as integral parts of broader networks. By leveraging existing tools such as GIS software, open-source programming packages, and publicly available data, appraisers can readily adopt the NVA framework. This makes the approach practical for widespread use while maintaining the rigor and transparency required in professional valuation.

To fully realize the potential of the NVA, future research should focus on large-scale case studies and empirical validation. This would not only refine the methodology but also demonstrate its effectiveness in accurately predicting market values. Finally, the NVA is not intended to supplant traditional valuation approaches but to complement them, adding a new dimension of analysis that captures the network effects critical to modern property markets.

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About the Authors

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Additional Resources

Suggested by the Y. T. and Louise Lee Lum Library

Appraisal Institute

- **Lum Library, Bibliographies [Login required]**
Subjects: | Hedonic models (26)
- **Publications—Appraisal Journal Articles**
 - Erin Kiella, Jennifer Pitts, and Christopher Yost-Bremin, "From a Theoretical Formula to a Defensible and Robust Model" (2025)
 - Matthew C. Trimble, "Regression Promises and Aggregation Bias Illusions: The Application of Market Delineation to Land Valuation Models" (2023)
- **Publications—Valuation Articles**
Woodward S. Hanson, "The Value of Networks" (2000)