Teaching the DiPasquale-Wheaton Model

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Abstract. The DiPasquale-Wheaton (1992) model graphically determines rental price, asset price, newly constructed stock, and total stock in a real estate market. Despite its frequent use in academic research, few textbooks exposit the model. I conjecture this is due in part to the difficulty of deriving its comparative static results. I derive a supply curve that simplifies graphical analysis and perform a complete graphical comparative static analysis. Although the main objective of this paper is to encourage pedagogical usage of the model, an Appendix provides a mathematical derivation of the comparative static results, which has not heretofore appeared in the literature.

Colwell (2002) reports that textbooks by DiPasquale and Wheaton (1996), Brueggeman and Fisher (1997), and Geltner and Miller (2001) contained the real estate model developed by DiPasquale and Wheaton (1992).[1] The only recently published books I have found that do so are Pirounakis (2013) and Geltner, Miller, Clayton, and Eichholtz (2014). Geltner, Miller, Clayton, and Eichholtz (2014) provide the comparative static effects of a demand increase and a capitalization rate decrease. Pirounakis (2013) only provides the four-quadrant graph to show the relations among the model's components. He performs no comparative statics. As Exhibit 1 documents, most textbooks neither cite nor use the model, while a smaller number cite but make no use of the model.

Despite the small number of textbooks that include discussion of the model, it has nevertheless been cited many times and featured in numerous academic articles. A Google Scholar search turned up 245 sources with citations to the DiPasquale-Wheaton article (1992) and 1,138 to the DiPasquale-Wheaton book (1996). Of the 245 article-citation sources, Exhibit 1 does not include those for which the following information was absent: title, English-language abstract, type of source (e.g., journal article, working paper, book, etc.), date, and citations in real estate textbooks. This left 175 citation sources, which are given in Exhibit 2 by source and year. It is clear that the professional interest in the article continues and even grows.

Concentrating on the academic journal articles that cite the DiPasquale-Wheaton article, I find that most are citations with no or only a brief comment. A few are complimentary but make no real use of the model (e.g., Mills, 1995; Akimov, Stevenson, and Zagonov, 2015). Some are complimentary and do use the model. Gat (2002, p. 5) says, "One of the best and most concise paradigms of the real estate market is the DiPasquale and Wheaton Four Quadrant model." He also applies the model, as will be discussed below. Lisi (2015, p. 87) calls the

Exhibit 1 Textbook Usage of the DiPasquale-Wheaton Model

Year	No Citation No Exposition	Citation No Exposition	Citation Exposition
1994	Fanning, Grissom & Pearson Larsen		
1995	Dasso, Shilling & Ring Jaffee & Sirmans, 3rd ed.		
1996	Gaddy & Hart, 4th ed.		DiPasquale & Wheaton
1997			Brueggeman & Fisher
1998	Ball, Lizieri & MacGregor Sindt Van Reken & Byrd	Corgel, Smith & Ling, 3rd ed.	
2000		Miles, Berens & Weiss, 3rd ed.	
2001	Brueggeman & Fisher, 11th ed. Schmitz & Brett	Corgel, Ling & Smith, 4th ed. Wang	Geltner & Miller
2002	Epley, Rabianski & Haney Shilling, 13th ed.		
2003	Clauretie & Sirmans, 4th ed. Kolbe, Greer & Rudner Larsen (a) Larsen (b) Wiedemer & Baker, 9th ed.	Greer & Kolbe, 5th ed.	
2004	Seabrooke, Kent & How		

Exhibit 1 (continued)
Textbook Usage of the DiPasquale-Wheaton Model

Year	No Citation No Exposition	Citation No Exposition	Citation Exposition
2005	Kahr & Thomsett	Ling & Archer	
		Miller & Geltner	
2006	Clauretie & Sirmans, 5th ed.		
	Kolbe & Greer, 6th ed.		
2007	Larsen with Carey & Carey	McDonald & McMillen	
2008	Brueggeman & Fisher, 13th ed.		
	Floyd & Allen		
2009	Baum, 2nd ed.		
	Cortesi, 5th ed.		
	Eldred, 6th ed.		
	Pecca		
	Ratcliffe, Stubbs & Keeping, 3rd ed.		
2010	Clauretie & Sirmans, 6th ed.	Brooks & Tsolacos	
	Huber & Messick, 7th ed.	McDonald & McMillen, 2nd ed.	
	Jacobus, 11th ed.		
2011	Brueggeman & Fisher, 14th ed.		
	Floyd & Allen, 10th ed.		
	Huber, Messick & Pivar, 5th ed.	Jowsey	
	McKenzie, Betts & Jensen, 6th ed.	Roche	

Exhibit 1 (continued)
Textbook Usage of the DiPasquale-Wheaton Model

Year	No Citation No Exposition	Citation No Exposition	Citation Exposition
2012	Dent, Patrick & Xu		
	Goddard & Marcum		
2013		Ling & Archer, 4th ed.	Pirounakis
2014	Clauretie & Sirmans, 7th ed.		
	Glickman		
	Jacobus, 12th ed.		Geltner et al., 3rd. ed.
	Tiwari & White		
2015	Jowsey		
	Manganelli		
2016	Brueggeman & Fisher, 15th ed.		

Exhibit 2 DiPasquale-Wheaton Article Citations, by Source and Year

	Article					
Year	Journal	Book	Book	Working Paper[a]	Thesis	Total
1992	1					1
1993			1	1		2
1994				2		2
1995	4			1		5
1996			1	1		2
1997	3		1			4
1998	2					2
1999	3	1		1		5
2000	3	1		1		5
2001	2			1		3
2002			1		1	2
2003	3		1			4
2004	4		1			5
2005	3					3
2006	3				1	4
2007	3			1		4
2008		1		3		4
2009	4		5	1		10
2010	5	1		5		11
2011	4		1	6	2	13
2012	4		2	8	2	16
2013	7		1	5		13
2014	10			7	2	19
2015	10		4	8	1	23
2016	7			5	1	13
Total	85	4	19	57	10	175

Notes: The source is Google Scholar (last accessed December 15, 2016).
[a] Includes conference papers.

DiPasquale-Wheaton model "the most popular macroeconomic model of the housing market." Some are pedagogical, usually providing an exposition of the model. For example, Achour-Fischer (1999) provides an interactive Excel version of the model, which employs specific functional forms and parameter values that allows the user to perform comparative static analyses.

The remaining articles employ the DiPasquale-Wheaton model in research. These articles fall into four broad categories: (1) those where the model is used as a framework for explanation of historical real estate development; (2) those where the model is used as a source of empirically testable hypotheses, sometimes providing extensions; (3) those that provide extensions of the model, with only theoretical analysis; and (4) those that provide extensions and use the extended model in empirical applications.

The following articles are examples of category 1, those where the model is used as a framework for explanation of historical real estate development. Renaud (1995) uses the model to study the Russian housing market during transition to a market economy. Hanink (1996) studies the geographical extent of office markets in the United States. Eng and Lee (2003) investigate the impact of financing and securitization on real estate markets and urban development in Singapore. Allen, Svsyannikova, Prazukin, and Worzala (2004) study the transition of the Russian housing market from one in which the government produced the most housing units to one in which the private market does so. Leung and Wang (2007) study the housing market in China, tracing the effect of various policies. Michelsen and Weiss (2010) study the development of the East German housing market after reunification. Lee, Shin, Kim, and Kim (2014) examine the Korean housing market before and after macroeconomic fluctuations.

The following articles are examples of category 2, those where the model is used as a source of empirically testable hypotheses, sometimes providing extensions. Kim and Yang (2006) estimate excess rates of return in the rental office market of Seoul. Constantinescu and Francke (2013), adding a lag structure to the model, track and analyze the development of the Swiss rental housing market. Wang and Kang (2014) study the effect on the housing prices of China's transition from a socialist system to a market economy. Lieser and Groh (2014) study how various socioeconomic characteristics affect commercial real estate investment.

The following articles are examples of category 3, those that provide extensions of the model, with only theoretical analysis. Colwell (2002) extends the model by endogenizing the capitalization rate; providing a non-proportional price-rent relation; and introducing lagged adjustment, expectations, and vacancies. Colwell also introduces a long-run supply function, which is important to this paper and will be discussed later. Gat (2002) develops a dynamic version of the model, which includes speculative asset value, construction lag, and stock adjustment. Adding parameter values, he simulates a reduction in the stock of space, a sudden population increase, and a gradual increase in real income. These exercises are not applied to any real economy, but they do show how these effects work themselves out over time. After a thorough discussion of the model and its shortcomings, essentially following Colwell (2002), Lisi (2015) extends the model to include search and matching in the housing market.

The following articles are examples of category 4, those that provide extensions and use the extended model in empirical applications. Viezer (1999) develops and estimates a real estate forecasting model for office markets, drawing on, among others, the DiPasquale-Wheaton model, and extending the model to include an endogenous cap rate and lags in adjustment. Gat (2000) provides specification, estimation, and simulation of the model and applies it to the Israeli housing market. Du Toit and Cloete (2004) develop a simulation model incorporating an equilibrium vacancy rate, and test it against data from the Pretoria, South Africa and Perth, Australia office markets. Chaney and Hoesli (2015) develop a dynamic version of the model and estimate it using Swiss multifamily residential data.

It is evident, therefore, that researchers find the model worthwhile for both theoretical and empirical analysis, while textbook authors generally do not choose to exposit it. The reason for this is likely the difficulty of graphically determining the equilibrium values of the model's endogenous variables under changes in the exogenous variables. This is a criticism noted by Colwell (2002).

It is also likely that the need for students to have some acquaintance with graphical supply and demand analysis causes textbook authors to eschew the model. All books contain discussions of supply and demand, but relatively few include supply and demand curves, which I simply call *supply-demand analysis*.

Nevertheless, there are several textbooks that contain supply-demand analysis, but not the DiPasquale-Wheaton model, namely, Brueggeman and Fisher (2001, 2008, 2011, 2016), Corgel, Smith, and Ling (1998), Corgel, Ling, and Smith (2001), Dasso, Shilling, and Ring (1995), Floyd and Allen (2008, 2011), Greer and Kolbe (2003), Huber, Messick, and Pivar (2011), Jacobus (2010, 2014), Jaffee and Sirmans (1995), Kolbe, Greer, and Rudner (2003), Kolbe and Greer (2006), Larsen (1994, 2003a, 2003b), McDonald and McMillen (2007, 2010), McKenzie, Betts, and Jensen (2011), Shilling, (2002), and Miller and Geltner (2005). Counting multiple editions only once, nine of these are real estate principles textbooks, for which the student audience might not be expected to have been exposed to supply-demand analysis, while five are real estate finance textbooks and two are real estate economics textbooks, for which it might more likely be the case that students would have had some exposure to supply-demand analysis.

The DiPasquale-Wheaton model, as exposited here, uses one demand curve and two supply curves, in addition to the relation of rental to asset price through the cap rate and the relation between the quantity of newly constructed stock and the existing stock through the depreciation rate. Therefore, expositing the DiPasquale-Wheaton model would not require much beyond what several textbooks already provide. Doing so, however, would expose students to a coherent real estate model widely used in theoretical and empirical analysis, a model that is missing from almost all real estate textbooks, even those that contain some supply-demand analysis.

The major purpose of this paper is to remove the difficulty of graphically obtaining the model's comparative static results in the hope that this will encourage authors to seriously consider including a presentation of the DiPasquale-Wheaton model in future textbooks. Although that is my major objective, I also present a complete mathematical derivation of the model's comparative static results in the Appendix. This does not, to my knowledge, exist in the published literature. In addition to providing a solid theoretical basis for the graphical analysis, advanced real estate and urban economics courses and textbooks could use the mathematical exposition.

I attain my major objective by introducing a long-run supply curve into the graphical treatment of the model, a suggestion made by Colwell (2002) but apparently not taken up by others.[2] This supply curve provides an "anchor" point for two of the endogenous variables from which the remaining endogenous variables may be determined. Although Colwell (2002) makes the suggestion, he does not follow up with a rigorous analysis, only showing how to determine the four endogenous variables and providing a tabulation of comparative static results on the capital stock and rent.[3]

In addition to changes in demand for space (and stock), supply of new stock, and the cap rate, I also provide a comparative static analysis of the depreciation rate. This last result is ignored by DiPasquale and Wheaton (1992, 1996), probably because it was thought to generate the same qualitative results as the cap rate. It was included in Colwell's (2002) tabulation of results, which conform to the results for rent and stock I derive. The results on new supply and asset price were not included in his tabulation, but I show they are in general ambiguous. I use an empirical argument to remove the ambiguity.

The paper proceeds as follows: A review of the DiPasquale-Wheaton model, including derivation of a new long-run supply curve; a complete graphical comparative static analysis of the model; a brief summary; and a complete mathematical comparative static analysis in the Appendix.

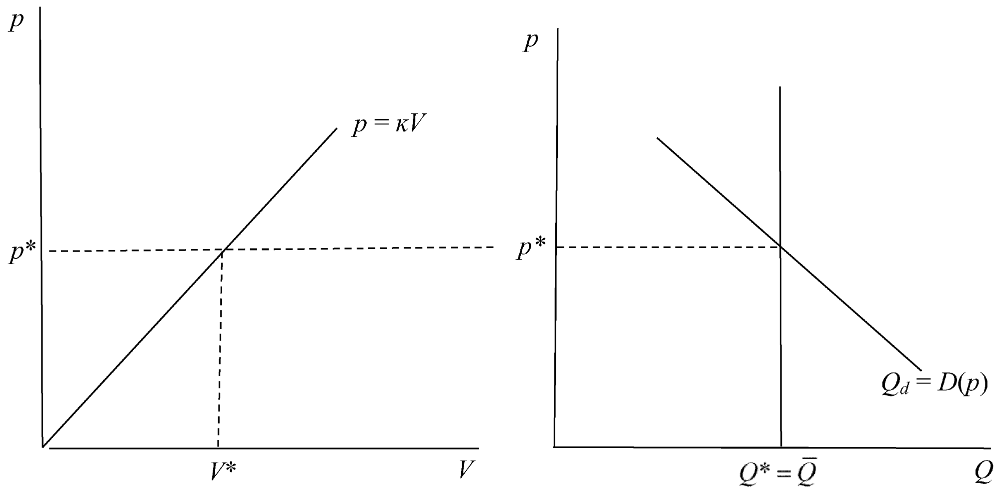
Review of the DiPasquale-Wheaton Model

THE RELATION AMONG DEMAND, EXISTING STOCK, RENT, AND PRICE

Following DiPasquale and Wheaton (1992, 1996), I exposit a long-run model. Although changes in vacancies serve as signals that a long-run adjustment is required, I nevertheless ignore the vacancy component in the long-run analysis. It can be included, but it complicates the model without providing much insight, at least for an introductory pedagogical exposition.[4]

The left-hand panel of Exhibit 3 shows the capital-cost relation between p, the price per unit of real estate space (here called the *rental price* or, simply, *rent*), and V, the price per unit of real estate capital (here called the *asset price* or, simply, *price*), where κ is the cap rate, which capitalizes rent into price. The quantity of real estate space demanded, Q_d, is a function of rent, p. Demand and the currently existing capital stock, $\overline{Q}$, determine the equilibrium rent, p^* and

Exhibit 3 Demand, Existing Stock, Rent, and Price



quantity Q^*. The right-hand panel of Exhibit 3 shows this. The cap-cost relation converts rent into price, so the equilibrium price is V^*, which is shown in the left-hand panel of Exhibit 3.

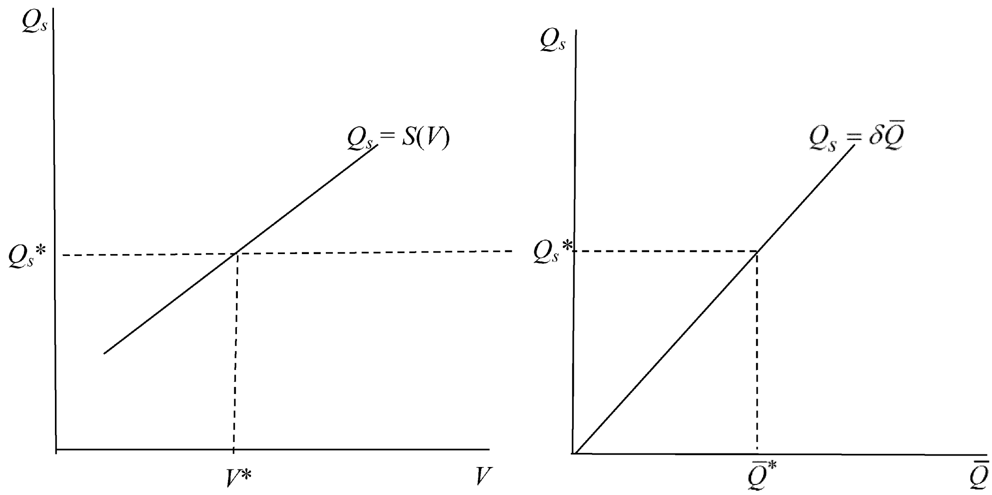
The Supply of New Stock and Its Relation to Existing Stock

New real estate stock is supplied by the construction industry, and, in general, that industry's supply function may be represented by $Q_s = S(V)$, where the subscript s on Q indicates supply. The construction industry responds to the asset price of stock, not to its rental price, and, as usually assumed, the supply curve is upward sloping, implying an increasing-cost industry.[5]

There exists previously built stock, which depreciates over time. If δ is the depreciation rate and $\overline{Q}$ is the existing stock, then $\delta\overline{Q}$ is the amount of stock that completely depreciates in any given period (e.g., a year). To maintain the stock, this amount must be replaced. If Q_s is the quantity of new stock constructed in a year and if $\Delta\overline{Q}$ is the net addition to the stock, then $\Delta\overline{Q} = Q_s - \delta\overline{Q}$. In long-run equilibrium, there is no excess supply or demand, meaning that the existing stock provides all real estate space demanded. Hence, in long-run equilibrium, $\Delta\overline{Q} = 0$, so $Q_s = \delta\overline{Q}$, which requires that new construction replace fully depreciated stock.

Exhibit 4 illustrates these points. I draw the long-run new-stock supply curve in the left-hand panel of Exhibit 4, not in the usual way, but with the axes reversed. Its upward slope indicates that as the asset price increases, the quantity supplied increases, and vice versa. The right-hand panel shows the relation between the existing stock and the amount of new construction that is required to maintain that stock. I draw Exhibit 4 under the assumption that the

Exhibit 4 New-Stock Supply in Long-Run Equilibrium



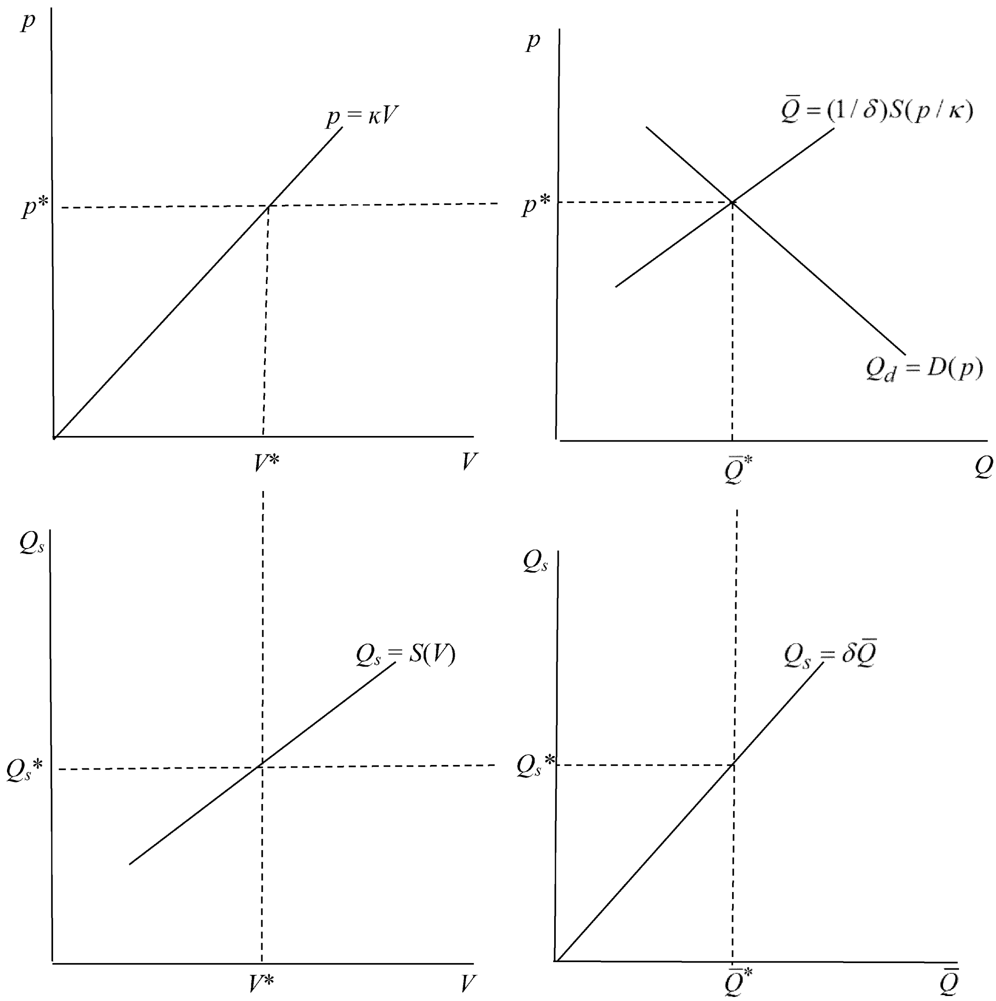
values shown on the axes are long-run equilibrium values. This is something I develop by putting Exhibit 3 and 4 together.

THE COMPLETE MODEL, INCLUDING DERIVATION OF THE LONG-RUN SUPPLY CURVE

Exhibit 5 provides a complete depiction of the model (ignore for now the upward sloping curve in the top-right quadrant). Given an initial stock, $\overline{Q}^*$, and demand, D, the equilibrium rent is p^*. This rental price, along with the given cap rate, κ, determines the equilibrium asset price V^*. The construction industry responds to this asset price by supplying Q_s^*, an amount that is just sufficient to replace the depreciated stock, $\delta\overline{Q}^*$. Note that I measure the flow quantity demanded and supplied in the top-right quadrant as the same as the stock quantity, which means that one unit of stock produces one unit of space.

Although the model is complete, it is difficult to perform the comparative static analysis because one has to find by trial and error the equilibrating values of the variables. To make this easier to do, I develop another long-run supply curve, one that depends on the rental price and includes replacement, as well as net additions to the stock ($Q_s = \delta\overline{Q} + \Delta\overline{Q}$). The new-stock supply curve in the bottom-left quadrant of Exhibit 5 has Q_s and V on the axes, but I want one that has $Q = \overline{Q}$ and p on the axes so that I can use it in the top-right quadrant. To obtain the desired supply curve, substitute p/κ for V and $\delta\overline{Q}$ for Q_s in $Q_s = S(V)$, getting $\delta\overline{Q} = S(p/\kappa)$, or $\overline{Q} = (1/\delta)S(p/\kappa)$, which is what I want. This is long-run supply, including both replacement of the fully depreciated stock and net additions to the stock. The equation of this supply function is redundant, in that the mathematical model does not need it. Its graph, however, is very important

Exhibit 5 Long-Run Equilibrium in the Space and Capital Markets



in that it eliminates the difficulty of obtaining the graphical comparative static results of the model.

Comparative Static Analysis of the Model

From a mathematical point of view, the model consists of the following four equations, to which I have added "shift parameters":

$$\overline{Q} = D(p, \theta_d) \quad (1)$$

$$Q_s = S(V, \theta_s) \quad (2)$$

$$p = \kappa V \tag{3}$$

$$Q_s = \delta \overline{Q}. \tag{4}$$

θ_d represents a vector of demand determinants other than rent. θ_s represents supply determinants other than asset price and expansion or contraction of the industry. Since I assume the new-stock supply curve is that of an increasing-cost industry, then I am embodying in the supply curve the increase in input prices as the industry expands (and the decrease as the industry contracts). I do not need to include shift parameters in the capital-cost equation or the stock-adjustment condition because their parameters are κ and δ.

Equations (1)–(4) are the structural equations of the model. The reduced form equations are the solution of the structural equations for the endogenous variables in terms of the exogenous variables:

$$p = p(\theta_d, \theta_s, \kappa, \delta) \tag{5}$$

$$Q_s = Q_s(\theta_d, \theta_s, \kappa, \delta) \tag{6}$$

$$V = V(\theta_d, \theta_s, \kappa, \delta) \tag{7}$$

$$\overline{Q} = \overline{Q}(\theta_d, \theta_s, \kappa, \delta). \tag{8}$$

Comparative static analysis consists of discovering how a change in one exogenous variable affects the endogenous variables, holding other exogenous variables constant. I do this graphically here, but the Appendix provides the mathematics. In the graphical analysis, variables with subscript zeroes are the exogenous variables held constant, while those with subscripts 1 and 2 indicate the initial and final values of the endogenous variables and the one exogenous variable whose effects I analyze. Also, I only analyze the effect of an increase in an exogenous variable, but a decrease in that variable will reverse the qualitative effects of an increase.

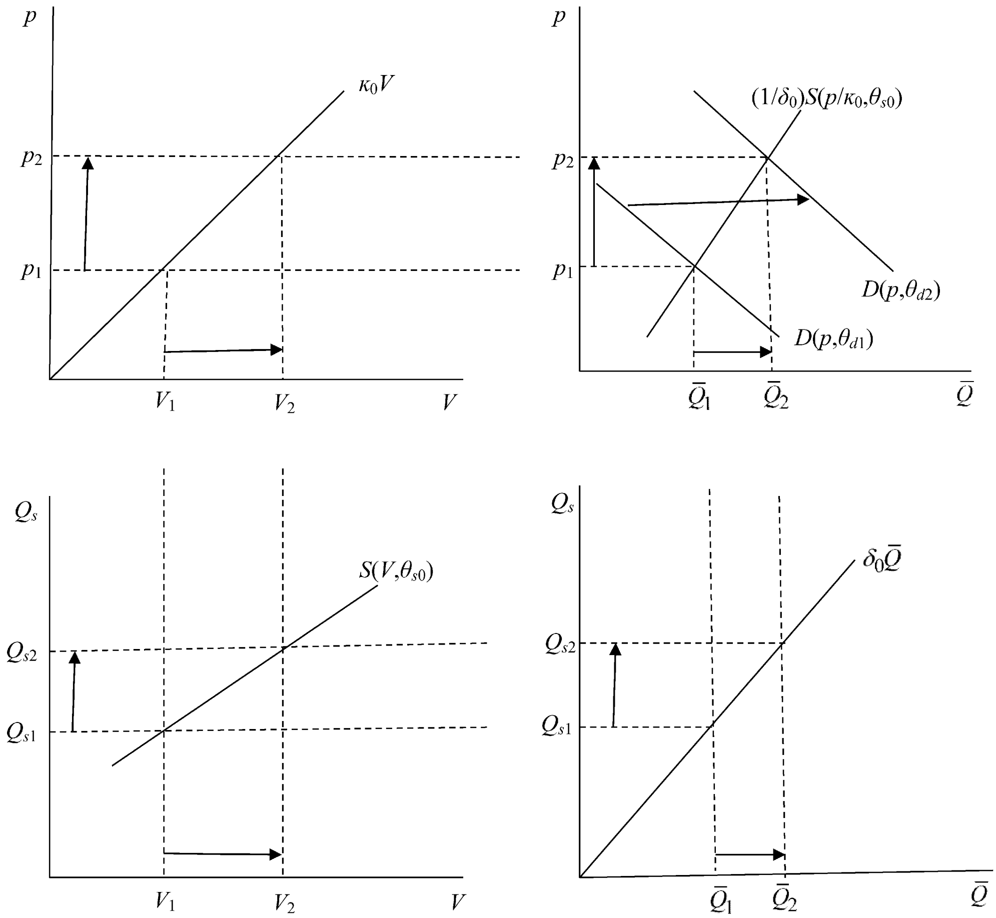
AN INCREASE IN DEMAND

An increase in demand is a shift to the right of the demand curve in the upper right quadrant of Exhibit 6. Since the supply curve is unchanged, equilibrium rent and quantity increase from p_1 to p_2 and $\overline{Q}_1$ to $\overline{Q}_2$. The increase in the rental price increases its asset price from V_1 to V_2. The increased asset price induces firms to produce more stock along the new-stock supply curve, from Q_{s1} to Q_{s2}. This increase in new stock must be sufficient to replace the fully depreciated stock and to provide a net increase in stock from $\overline{Q}_1$ to $\overline{Q}_2$.

AN INCREASE IN THE SUPPLY OF NEW STOCK

Exhibit 7 shows a supply increase in both the top-right quadrant and the bottom-left quadrant. In the top-right quadrant, I show the supply increase in the usual way as a shift of the supply curve to the right. In the bottom-left quadrant,

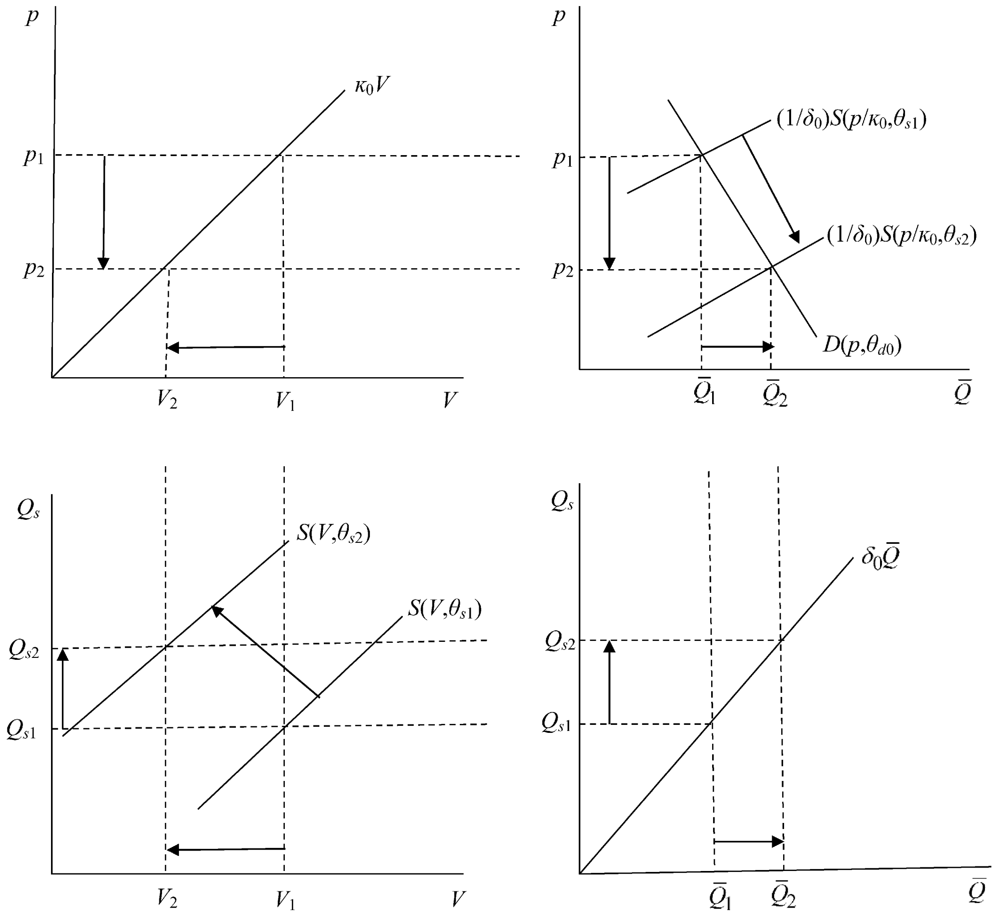
Exhibit 6 Comparative Static Effects of an Increase in Demand



however, the supply curve shifts to the left. This is due to the fact that I reversed the axes from the usual presentation of supply.

Whatever the cause of the supply increase, the result is a decrease in equilibrium rent from p_1 to p_2, and an increase in equilibrium quantity, from $\overline{Q}_1$ to $\overline{Q}_2$, both of which are shown in the top-right quadrant. The decrease in rent results in a decrease in price from V_1 to V_2, shown in the top-left quadrant of Exhibit 7. The decrease in price would by itself cause a decrease in quantity supplied along the leftward-shifted supply curve in the bottom-left quadrant, but the increase in the supply curve outweighs the downward movement along the curve, resulting in an increase in new construction from Q_{s1} to Q_{s2}. It is easy to see that this must be the result from the change in Q in the top-right quadrant. The increase in new production replaces fully depreciated stock, as well as resulting in a net increase in stock from to $\overline{Q}_1$ to $\overline{Q}_2$.

Exhibit 7 Comparative Static Effects of an Increase in Supply

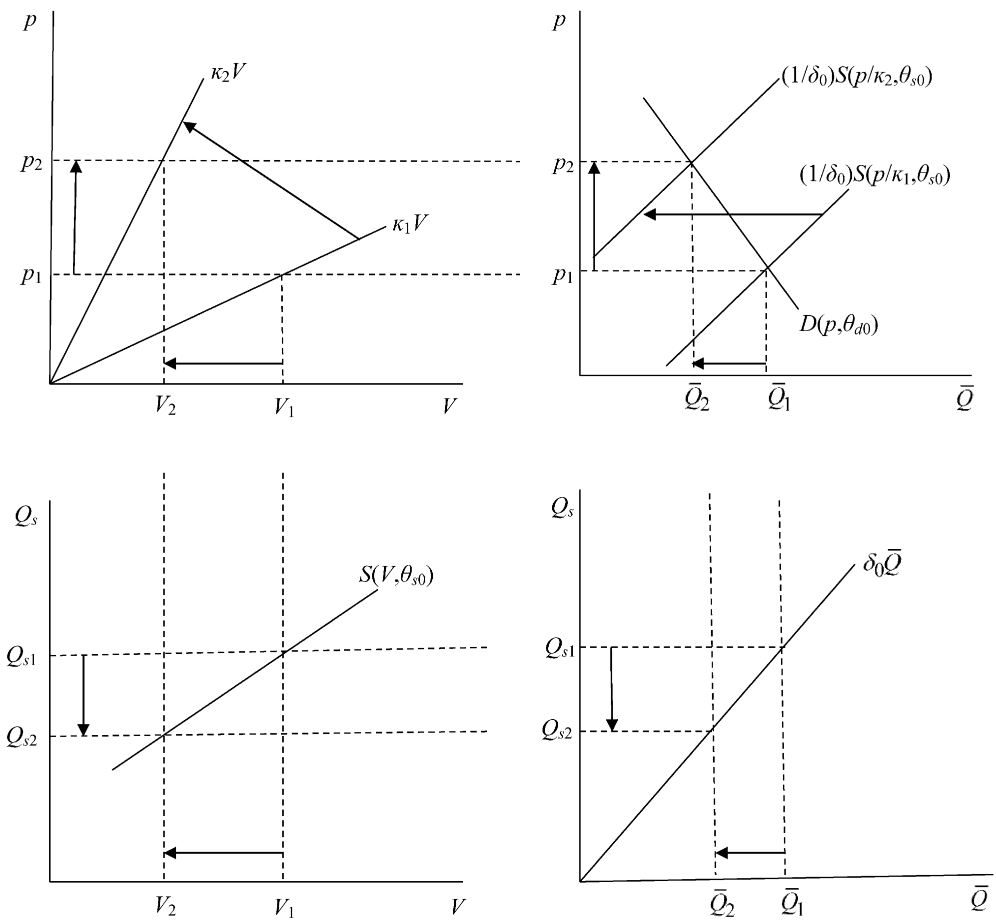


AN INCREASE IN THE CAP RATE

Exhibit 8 shows the effects of an increase in the cap rate, due to a factor other than the depreciation rate. (Although the cap rate includes the depreciation rate as a component, a change in the depreciation rate is more complicated and I treat it separately later.) This affects both the supply curve in the top-right quadrant and the capital-cost line in the top-left quadrant. The capital-cost line pivots upward. An increase in the cap rate decreases $p/\kappa = V$, other things equal, which shifts the supply curve in the upper right quadrant leftward, while being represented as a movement along the new stock supply curve in the lower left quadrant.

Starting in the top-right quadrant in Exhibit 8, the increased cap rate decreases supply, which causes an increase in equilibrium rent from p_1 to p_2, and a

Exhibit 8 Comparative Static Effects of an Increase in the Cap Rate

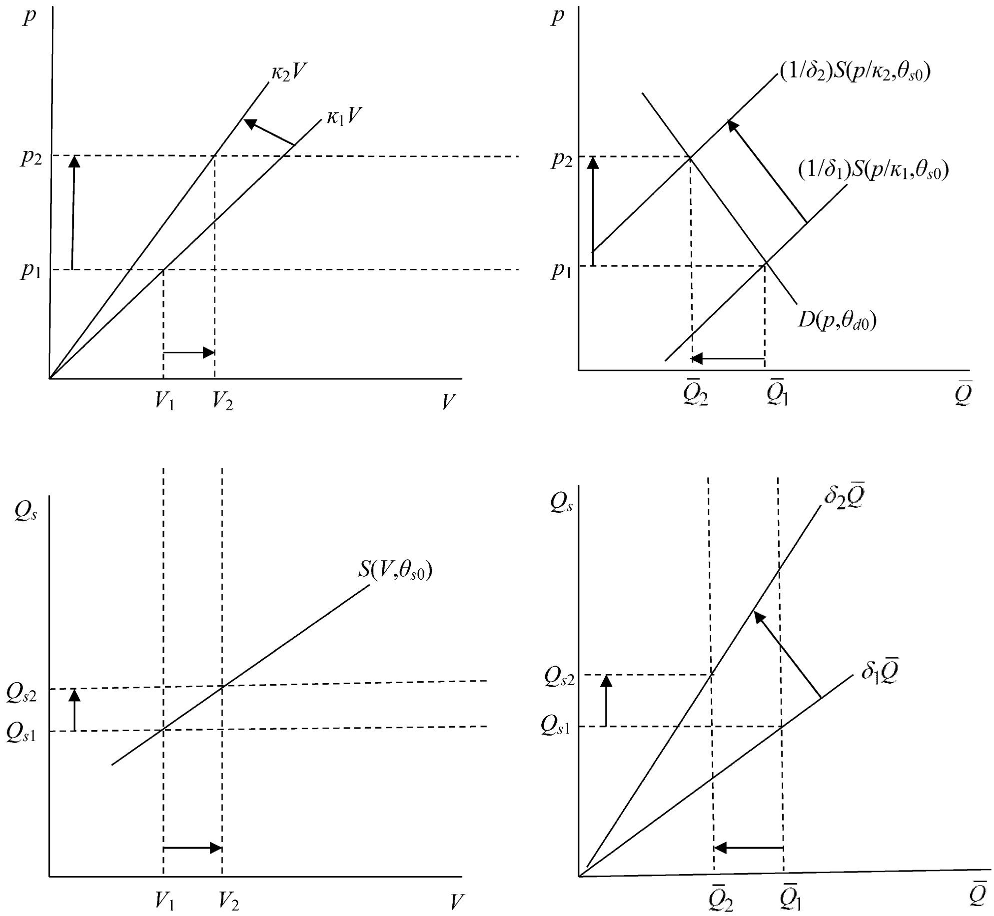


decrease in equilibrium quantity from $\overline{Q}_1$ to $\overline{Q}_2$. By itself, the increase in rent would increase the asset price. In this case, however, the increase in the cap rate pivots the capital-cost line upward sufficiently to reduce the asset price. That this must be the case is seen in the bottom two quadrants, which show the decrease in quantity supplied required in the top-right quadrant. Production decreases because the asset price decreases. The net decrease in production is brought about by not replacing fully depreciated stock and possibly by abandonment and demolition of not fully depreciated stock.

AN INCREASE IN THE DEPRECIATION RATE

Analysis of the deprecation rate is complicated by the fact that it appears in the equilibrium condition, $Q_s = \delta\overline{Q}$, and in the cap rate, κ, because the depreciation rate, δ, is one of the terms in κ. It also appears in the long-run supply curve

Exhibit 9 Comparative Static Effects of an Increase in the Depreciation Rate



used in the upper-right quadrant of the graphical presentation of the comparative static results. Thus, when the depreciation rate changes it causes changes in three curves in Exhibit 9.

An increase in the rate of depreciation causes the long-run supply curve in the top-right quadrant to shift to the left (i.e., supply decreases). If $\delta_2 > \delta_1$, then $1/\delta_2 < 1/\delta_1$, which would shift the curve leftward. Note, however, that $\kappa_2 > \kappa_1$ because δ is one of the components of the cap rate. This also lowers p/κ, which would be a move down the supply curve in the bottom-left quadrant in Exhibit 9, but which would entail a leftward shift in the supply curve in the top-right quadrant.

The decrease in supply causes equilibrium rent to rise from p_1 to p_2 and equilibrium quantity to fall from $\overline{Q}_1$ to $\overline{Q}_2$. This implies a corresponding decrease in stock in the bottom-right quadrant of Exhibit 9, in conjunction with an upward pivot of the $\delta\overline{Q}$ curve due to the increase in the depreciation rate from δ_1 to δ_2.

So far, this is straightforward, but I still must explain the effects on Q_s and V, which are unfortunately not straightforward. In general, the qualitative effects of an increase in the depreciation rate on these variables are ambiguous. In other words, it is possible to produce the effects on p and $\overline{Q}$ with an increase in V and a resulting increase in Q_s, which is what Exhibit 9 shows, or a decrease in V and a resulting decrease in Q_s. To get the latter result, I must shift the supply curve in the top-right quadrant less to the left than shown in Exhibit 9, so that p still rises but produces a lower V on the $\kappa_2 V$ curve in the top-left quadrant of Exhibit 9. This, in turn, will generate a lower Q_s in the bottom-left quadrant.

When there is a theoretically ambiguous comparative static result, to get an unambiguous result, I must either introduce a more restrictive assumption or use an empirical argument. I employ the latter approach. V and Q_s are directly related to δ if $\overline{Q} + \delta D_p V > 0$ (see the Appendix), where D_p is the rent-slope of the demand function, which is negative, while the other variables are positive. Under reasonable magnitudes for these variables, the magnitude of $\overline{Q}$ will greatly exceed that of the second term, so that the positivity of $\overline{Q}$ will outweigh the negativity of the other term.

To illustrate this, I adapt a numerical example from DiPasquale and Wheaton (1996, pp. 8–10). The equations of the model in my notation are:

$$\overline{Q} = \theta_d(400 - 10p) \tag{9}$$

$$Q_s = 0.2(V - \theta_s) \tag{10}$$

$$p = \kappa V \tag{11}$$

$$Q_s = \delta\overline{Q}. \tag{12}$$

Let $\theta_d = 10$ (million office workers per year, a demand determinant for office space), $\theta_s = 200$ (dollars per square foot of office space per year, a supply determinant of office space), $\kappa = 0.05$, and $\delta = 0.01$. Then, solving equations (9)–(12) yields $\overline{Q} = 2.4$ billion square feet, $p = \$16$ per sq. ft. per year, $V = \$320$ per sq. ft., and $Q_s = 24$ million sq. ft. per year. Given these results and the assumed parameter values, $D_p = -100$, so $\overline{Q} + \delta D_p V = 2{,}400 + (0.01)(-100)(320) = 2{,}400 - 320 > 0$ (the unit in which both terms are measured is millions of square feet).[6]

Under this empirical assumption, I find that, in addition to p being directly related to δ and $\overline{Q}$ being inversely related to δ, I now have V and Q_s directly related to δ. It may seem strange that, although the equilibrium stock contracts under an increase in the depreciation rate, the equilibrium amount of new construction increases. This means that to maintain the now lower quantity of stock, builders must nevertheless build more new stock per year. Returning to

Exhibit 10 Comparative Static Results of the Real Estate Market Model

	Endogenous Variables			
Exogenous Variables	p	Q_s	V	$\overline{Q}$
θ_d	+	+	+	+
θ_s	−	+	−	+
κ	+	−	−	−
δ	+	+[a]	+[a]	−

Note:
[a] For reasonable numerical values.

the numerical example, suppose the depreciation rate rises from 0.01 to 0.02, then the new equilibrium $\overline{Q}$ is 1.75 billion sq. ft., and the new Q_s is (0.02)(1,750,000,000) = 35,000,000 sq. ft. per year, which is larger than the 24,000,000 resulting from the lower depreciation rate.

Summary

The main purpose of this paper is to kindle interest by textbook authors in the DiPasquale-Wheaton model as a pedagogical tool. I conjecture that one reason that only a couple of textbooks use the model is the difficulty of obtaining the comparative static results graphically. To address that problem, I adopt a suggestion of Colwell (2002) to include a supply curve in the upper-right quadrant of the four-quadrant analysis. Such a curve captures both the construction of net new stock, as well as replacement of completely depreciated stock. From a graphical viewpoint, it, coupled with the demand curve for space (and stock), provides an "anchor" point from which the two endogenous variables, rent and total stock, are determined. Given those two variables, it is a simple task graphically to determine the remaining two endogenous variables, asset price and newly constructed stock. I exposit a complete graphical comparative static analysis of the model.

In the Appendix, I present a mathematical comparative static analysis of the model, not heretofore available. Among the comparative static results is one involving a change in the depreciation rate, which has not previously been treated graphically. I find that the effects of a change in the depreciation rate on the supply of new stock and its asset price are ambiguous in general. To remove the ambiguity, I posit an empirical argument.

In Exhibit 10, I summarize the comparative static results of the model. A plus sign denotes a direct effect of the exogenous variable on the endogenous variable, while a minus sign denotes an inverse effect. Demand is the only case for which the exogenous effect is directly related to all of the endogenous variables. A shift in the new stock supply curve is inversely related to rental and asset prices and directly related to new construction and the existing stock. A change in the cap rate (not due to depreciation change) is directly related to rent but inversely related to the other endogenous variables. A change in the depreciation rate is directly related to the rental and asset prices and to new construction but inversely related to the existing stock. The effects on Q_s and V depend on our assumption that the magnitude of $\overline{Q}$ is very large relative to $\delta D_p V$. Rental and asset prices move together in all cases except for a change in the cap rate.

Appendix
Mathematical Comparative Static Analysis of the Real Estate Market Model

PRELIMINARIES

The model consists of Equations (1)–(4) in the text. I begin by totally differentiating these equations, where a subscript on a function represents differentiation, getting:

$$d\overline{Q} = D_p dp + D_{\theta_d} d\theta_d \tag{A.1}$$

$$dQ_s = S_V dV + S_{\theta_s} d\theta_s \tag{A.2}$$

$$dp = \kappa dV + V d\kappa \tag{A.3}$$

$$dQ_s = \delta d\overline{Q} + \overline{Q} d\delta, \tag{A.4}$$

where $D_p < 0$, $D_{\theta_d} > 0$, $S_V > 0$, and $S_{\theta_s} > 0$. Rewriting these equations by isolating the exogenous variables and writing the resulting equation system in matrix notation, I obtain:

$$\begin{bmatrix} -D_p & 0 & 0 & 1 \\ 0 & 1 & -S_V & 0 \\ 1 & 0 & -\kappa & 0 \\ 0 & 1 & 0 & -\delta \end{bmatrix} \begin{bmatrix} dp \\ dQ_s \\ dV \\ d\overline{Q} \end{bmatrix} = \begin{bmatrix} D_{\theta_d} d\theta_d \\ S_{\theta_s} d\theta_s \\ V d\kappa \\ \overline{Q} d\delta \end{bmatrix}. \tag{A.5}$$

Let $\mathfrak{D}$ be the determinant of the 4×4 matrix above. Upon evaluating that determinant, I have:

$$\mathfrak{D} = S_V - \delta D_p \kappa > 0. \tag{A.6}$$

COMPARATIVE STATICS OF *p*

$$\mathfrak{D} dp = \begin{vmatrix} D_{\theta_d} d\theta_d & 0 & 0 & 1 \\ S_{\theta_s} d\theta_s & 1 & -S_V & 0 \\ V d\kappa & 0 & -\kappa & 0 \\ \overline{Q} d\delta & 1 & 0 & -\delta \end{vmatrix} = \kappa \overline{Q} d\delta + S_V V d\kappa - \kappa S_{\theta_s} d\theta_s + \delta \kappa D_{\theta_d} d\theta_d. \tag{A.7}$$

Hence,

$$\frac{\partial p}{\partial \theta_d} = \frac{\delta\kappa D_{\theta_d}}{\mathfrak{D}} > 0,\ \frac{\partial p}{\partial \theta_s} = -\frac{\kappa S_{\theta_s}}{\mathfrak{D}} < 0,\ \frac{\partial p}{\partial \kappa} = \frac{S_V V}{\mathfrak{D}} > 0,\ \frac{\partial p}{\partial \delta} = \frac{\kappa\overline{Q} + S_V V}{\mathfrak{D}} > 0. \quad \text{(A.8)}$$

In this and the following results for a change in δ, the second term in the numerator appears because $d\kappa = d\delta$.

COMPARATIVE STATICS OF Q_s

$$\begin{aligned}\mathfrak{D}dQ_s &= \begin{vmatrix} -D_p & D_{\theta_d}d\theta_d & 0 & 1 \\ 0 & S_{\theta_s}d\theta_s & -S_V & 0 \\ 1 & Vd\kappa & -\kappa & 0 \\ 0 & \overline{Q}d\delta & 0 & -\delta \end{vmatrix} \\ &= S_V\overline{Q}d\delta - \delta\kappa D_p S_{\theta_s}d\theta_s + \delta S_V D_{\theta_d}d\theta_d + \delta D_p S_V V d\kappa. \end{aligned} \quad \text{(A.9)}$$

Hence,

$$\begin{aligned}&\frac{\partial Q_s}{\partial \theta_d} = \frac{\delta S_V D_{\theta_d}}{\mathfrak{D}} > 0,\ \frac{\partial Q_s}{\partial \theta_s} = -\frac{\delta\kappa D_p S_{\theta_s}}{\mathfrak{D}} > 0,\ \frac{\partial Q_s}{\partial \kappa} = \frac{\delta D_p S_V V}{\mathfrak{D}} < 0, \\ &\frac{\partial Q_s}{\partial \delta} = \frac{S_V\overline{Q} + \delta D_p S_V V}{\mathfrak{D}} \gtrless 0. \end{aligned} \quad \text{(A.10)}$$

COMPARATIVE STATICS OF V

$$\mathfrak{D}dV = \begin{vmatrix} -D_p & 0 & D_{\theta_d}d\theta_d & 1 \\ 0 & 1 & S_{\theta_s}d\theta_s & 0 \\ 1 & 0 & Vd\kappa & 0 \\ 0 & 1 & \overline{Q}d\delta & -\delta \end{vmatrix} = -S_{\theta_s}d\theta_s + \overline{Q}d\delta + \delta D_p V d\kappa + \delta D_{\theta_d}d\theta_d. \quad \text{(A.11)}$$

Hence,

$$\frac{\partial V}{\partial \theta_d} = \frac{\delta D_{\theta_d}}{\mathfrak{D}} > 0,\ \frac{\partial V}{\partial \theta_s} = -\frac{S_{\theta_s}}{\mathfrak{D}} < 0,\ \frac{\partial V}{\partial \kappa} = \frac{\delta D_p V}{\mathfrak{D}} < 0,\ \frac{\partial V}{\partial \delta} = \frac{\overline{Q} + \delta D_p V}{\mathfrak{D}} \gtrless 0. \quad \text{(A.12)}$$

COMPARATIVE STATICS OF $\overline{Q}$

$$\begin{aligned}\mathfrak{D}dV &= \begin{vmatrix} -D_p & 0 & 0 & D_{\theta_d}d\theta_d \\ 0 & 1 & -S_V & S_{\theta_s}d\theta_s \\ 1 & 0 & -\kappa & Vd\kappa \\ 0 & 1 & 0 & \overline{Q}d\delta \end{vmatrix} \\ &= \kappa D_p\overline{Q}d\delta + D_p S_V V d\kappa + S_V D_{\theta_d}d\theta_d - \kappa D_p S_{\theta_s}d\theta_s. \end{aligned} \quad \text{(A.13)}$$

Hence,

$$\frac{\partial \overline{Q}}{\partial \theta_d} = \frac{S_V D_{\theta_d}}{\mathfrak{D}} > 0, \frac{\partial \overline{Q}}{\partial \theta_s} = -\frac{\kappa D_p S_{\theta_s}}{\mathfrak{D}} > 0, \frac{\partial \overline{Q}}{\partial \kappa} = \frac{D_p S_V V}{\mathfrak{D}} < 0,$$

$$\frac{\partial \overline{Q}}{\partial \delta} = \frac{\kappa D_p \overline{Q} + D_p S_V V}{\mathfrak{D}} < 0. \tag{A.14}$$

Signing $\partial Q_s/\partial \delta$ and $\partial V/\partial \delta$

Both of these terms are positive if $\overline{Q} + \delta D_p V > 0$. I argue in the text that $\overline{Q}$ is very likely to be much larger in magnitude than $\delta D_p V$, in which case $\overline{Q} + \delta D_p V > 0$.

Endnotes

1. Fisher (1992) independently developed a similar model, but he did not provide graphical or mathematical comparative static analysis. Colwell (2002, p. 24) notes that the Brueggeman-Fisher text used Fisher's version of the model.
2. It is included in Lisi (2015) but only as a review of Colwell (2002).
3. Colwell (2002) provides several other "tweaks" to the model, namely, distinguishing between the capitalization rate and the reciprocal of the gross income multiplier; endogenizing the capitalization rate; and introducing short-run adjustments, expectations, and vacancies. Lisi (2015) reviews these extensions, and he goes on to integrate the model with search and matching models.
4. DiPasquale and Wheaton (1992) ignore vacancies, while Fisher (1992, p. 167) and Colwell (2002, pp. 33–36) include them.
5. Fisher (1992) assumes a constant-cost industry.
6. It is not clear what geographical unit DiPasquale and Wheaton (1992) have in mind. Ten million office workers is a large number, but if I scale it down to 1,000 office workers, nothing changes except that the two terms are now measured in thousands of square feet. A Q of 2.4 million square feet of office space is about half the size necessary to meet one criterion of Garreau's (1991, p. 6) definition of an edge city.

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