Effects of Planning and Policy Decisions on Residential Land Use in Singapore

by

Noel R. Davis

B.S.A.D., Massachusetts Institute of Technology (2006)
M.Arch., Illinois Institute of Technology (2008)

Submitted to the Department of Architecture
in partial fulfillment of the requirements for the degree of

Master of Science in Building Technology

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2012

Author . . . .
Department of Architecture
May 11, 2012

Certified by . . . .
John E. Fernández
Associate Professor of Architecture and Building Technology
and Engineering Systems
Thesis Supervisor

Accepted by . . . .
Takehiko Nagakura
Associate Professor of Design and Computation
Chair of the Department Committee on Graduate Students

Thesis Committee

Supervisor . . . .

John E. Fernández, MArch
Associate Professor of Architecture and Building Technology
and Engineering Systems
Massachusetts Institute of Technology

Reader . . . .

Lawrence Vale, SMArchS, DPhil
Ford International Professor of Urban Design and Planning
Massachusetts Institute of Technology

Reader . . . .

David Geltner, PhD
Professor of Real Estate Finance and Engineering Systems
Director of Research, Center for Real Estate
Massachusetts Institute of Technology

Reader . . . .

P.J. Lamberson, PhD
Senior Lecturer, Management and Organizations
Senior Research Associate, Institute on Complex Systems
Kellogg School of Management, Northwestern University

Effects of Planning and Policy Decisions on Residential Land Use in Singapore

by

Noel R. Davis

Submitted to the Department of Architecture
on May 11, 2012, in partial fulfillment of the
requirements for the degree of
Master of Science in Building Technology

Abstract

A study of current land use in Singapore shows that through effective long-term space planning, the island city-state has maintained an adequate stock of developable residential land to meet its most ambitious maximum population projections.

Two indicators of residential land use efficiency are defined: Residential Land Use Footprint, Λ_r, measures the per-capita residential land requirement; Mean Residential Redevelopment Time, T_r, defines the weighted average time for the government to redevelop a typical plot of residential land. A dynamic stock-and-flow model is described to calculate the historical residential land use footprint and mean residential redevelopment time between 1990 and 2011.

Finding that the primary driver of residential land use footprint is the change in household occupant density, a System Dynamics model is developed to simulate the historical housing price, supply response, and occupant density. Using a stock management structure to modulate housing supply and commodity dynamics structures to determine housing prices, the calibrated model is used to forecast the behavior trends of several housing policy and population growth scenarios.

Thesis Supervisor: John E. Fernández
Title: Associate Professor of Architecture and Building Technology
and Engineering Systems

Acknowledgments

I would like to thank my thesis advisor, John Fernández, for his guidance and support through the process of exploring, defining, and carrying out the research presented here.

Additionally, I could not have completed this study without the feedback, encouragement, and advice of my thesis committee members, Larry Vale, David Geltner, and P.J. Lamberson.

This project was made possible through the collaboration between MIT and the newly founded Singapore University of Technology and Design (SUTD), and the ambitious research agenda and generous support of the International Design Center (IDC).

Finally, to my wife, Leah, my parents, my family and friends, thank you for always being there to support my academic endeavors.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Meeting the needs of a growing global population with the finite physical resources available on the planet will surely be one of the greatest challenges for human civilization in the coming generations. Current, unprecedented rates of urbanization introduce both difficulties and opportunities to the global resource management effort [1]. With increased quality of life and better economic opportunities, urban citizens—especially in developing regions—tend to demand more per-capita-resources than their rural counterparts. However, cities offer numerous economy-of-scale advantages that facilitate and improve the delivery of quality of life improving services [2]. Large scale centralization and extensive infrastructure allow cities to process and distribute resources efficiently, while high population densities put consumers physically close to points of production [3].

Because of the economic opportunities and advantages that cities offer, the current trend of global urbanization is unlikely to slow in the near future. Given this inevitable growth in urban population, cities have an ever greater responsibility to provide for their citizens as efficiently as possible, through management of the limited physical resources available to them. But in order to make informed policies, decision makers require information about the resource-related consequences of their actions.

Historically, reliable quantitative projections of various policies' resource implications have rarely been available at the time these decisions are made. But advances in data availability, methodologies for resource accounting and modeling, and computing resources have made this type of policy evaluation modeling widely accessible. One successful example of quantitative models being used in the formation of policy is the Convention on Long-Range Transboundary Air Pollution (CLRTAP) in the mid-1990s, which utilized the Regional Acidification Information and Simulation (RAINS) model to assess the geographical effects of air pollutants across Europe [4, 5, 6]. Similarly, the intention of this study is to provide insight and information to policy makers about the potential resource use implications of various planning and policy decisions being considered today.

1.1 Land as a Limited Resource

The term ‘physical resources’ is broad, encompassing nearly all of the natural resources required to support human activity: water, energy, biomass, construction materials, industrial materials, products, and land. While many of the most pressing global resource issues are related to energy and water, this study investigates the use and management of urban land—specifically residential land—as a primary physical resource.

The overall progress of human civilization can be viewed through the lens of land use transformation [7]. Beginning with hunter-gatherer populations who adapted their lifestyles to fit their environment, civilization began when humans started to transform the landscape to suit their needs. First, the land was cultivated for agriculture, then more intensely developed for industrial purposes, and most recently repurposed to support service-based economies. Krausmann, et al. identify these stages of development as sociometabolic regimes, each with their own particular resource requirement profiles [8]. In this way, the development of land is shown to be directly connected to the physical resource demands of a society.

On the small island city-state of Singapore, a nearly complete land use transformation from primary native vegetation to urban uses has occurred in just the last 200 years, see Figure 1-1. Because of its small size, limited resources, definitive boundaries, and well-documented rapid urbanization, Singapore is considered to be one of the best locations to study the drivers and effects of urban growth and resource management.

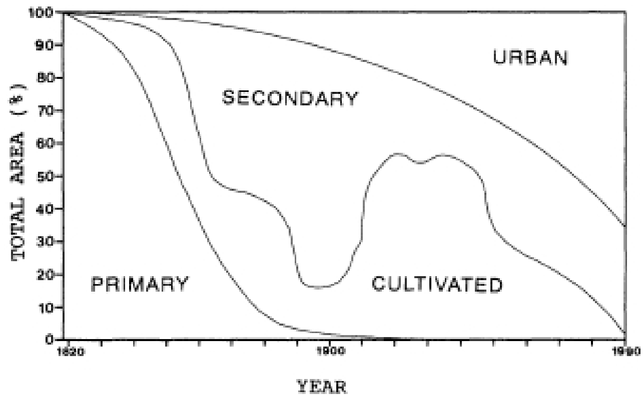

Figure 1-1: Singapore land use transformation, 1820–1990 [9]

1.2 Singapore: Population, Housing, and a Shortage of Land

In the last half-century Singapore has advanced from a struggling new nation to one of the world's most competitive economies [10]. Behind every aspect of its development has been a dedicated focus on long-term planning. Constrained by a lack of natural resources—land, energy, water, materials—Singapore's rise is a study in well-executed resource management. In the cases of energy, water and materials, Singapore's strong economic growth has made procurement of these resources from other nations possible. In the case of land, however, despite significant reclamation efforts the ultimate resource is limited, and long-term growth is largely an issue of land management over acquisition [11].

Effective residential land management is a necessity for Singapore as it pursues a larger population, stronger economy and ever higher quality of life for its citizens. Historically in Singapore, increasing quality of life has been measured by improvements in housing [12].

The Singapore housing landscape is dominated by owner-occupied public housing.

Early in its independence, the government identified home ownership as a key tenet in its goal of getting people invested in the future of the nation. In 1966 the Urban Redevelopment Authority (URA) was formally established and given widespread authority to repossess and redevelop land, and in concert with the Housing Development Board (HDB), a 30 year campaign of slum clearing and new public housing development ensued [13].

Between 1965 and 1990 Singapore's HDB built over 670,000 units of public housing to alleviate poor living conditions and an extreme housing shortage. By 1990, 87% of the resident population lived in HDB housing. Since then, however, a growing non-resident population and increasing wealth among residents have spawned a burgeoning, yet highly regulated private market. Today, private units make up 22% of Singapore's total housing stock [14]. The private market is dominated by non-residents and the wealthiest bracket of Singaporeans, but there is significant aspiration for private housing among rising upper middle class residents.

1.2.1 Public New Construction Market

Initial HDB offerings were in the form of rental units, targeted to the lowest income citizens, who were in dire need of adequate housing. Once this segment of the population was housed, home ownership became the HDB's priority, and focus was given to making new homes affordable and available to all residents. In order to house the neediest residents first, the HDB introduced a maximum income ceiling, and gave priority to larger families. For households meeting these requirements, modest new units were made affordable for purchase through HDB subsidies and generous financing terms [15].

Gradually, as the needs of the lowest income groups were satisfied, the requirements for purchase of a new HDB flat were relaxed to include married couples without children, and households with higher incomes. By the mid 1980s Singapore's housing shortage was all but eliminated, and the HDB's focus shifted from immediate provision to quality improvement. Today, an increasingly affluent population demands higher quality housing, and the top end of the HDB market now overlaps the lower-end private market—non-landed apartments and condominiums. To compete with the private market, the HDB has continued to raise the income ceiling, given priority to first-time home buyers, and steadily improved the quality and amenities of high-end HDB units.

1.2.2 Public Resale Market

Through 30 years of provision-focused housing development, early HDB flat owners' families matured, incomes increased significantly, and a desire for better HDB units grew among many residents. With fewer new units being built each year, a means for trading up to a better unit became necessary. It was during the early 1990s that a viable resale market for public housing units was established [16]. Allowing residents to buy and sell existing HDB units on an open market created opportunities for relocation, upgrading, and capital gains through equity growth.

Initially, demand for resale flats was quite low because suitable financing measures were not in place to make resale purchases affordable. To spur demand, two types of policies were introduced in the resale market. Favorable financing terms were granted to resale purchases in the form of lower down payment requirements, and the use of one's Central Provident Fund (CPF)—Singapore's mandatory savings and retirement vehicle—was allowed. Also subsidies, called CPF Grants, were offered for resale transactions. The initial implementation of these policies was largely responsible for the real estate bubble of 1996, and to quell speculative purchasing financing terms were restricted and a new type of policy—the "Stamp Duty"—was levied on all resale transactions. In addition, the required Minimum Occupancy Period (MOP) in an HDB unit between sales was increased. Through a fairly stagnant period, from 2003-2007, policies prohibiting the sublease of entire HDB units were relaxed to reduce public resale supply [17]. In the past two years, with public resale prices skyrocketing, this trend has reversed and there is now increasing restriction on subleased units.

In short order, the public resale market has become the largest sector of residential real estate in Singapore, with transactions on the order of 3%-8% of the total stock per year [18]. Since the first quarter of 1990, the HDB has maintained a quarterly index

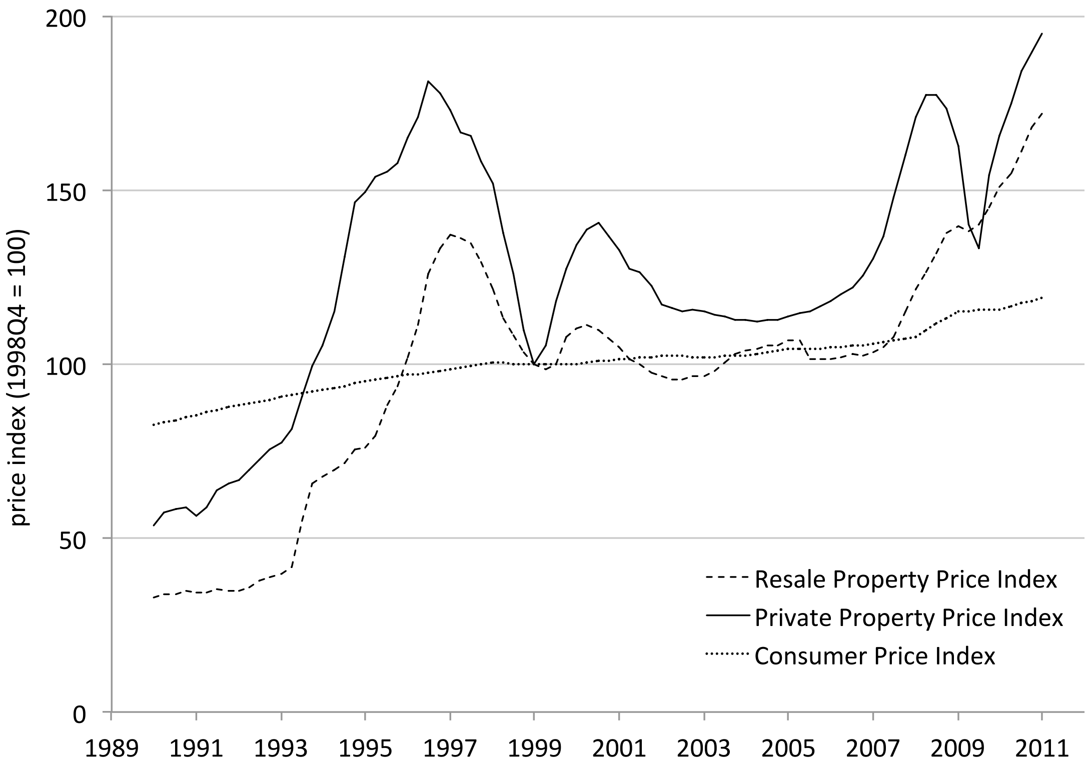

Figure 1-2: Singapore Residential and Consumer Price Indexes, 1990–2011

of public resale prices. As HDB resales represent a significant portion of Singapore's total housing market activity, the HDB Resale Price Index serves as a critical indicator of the overall affordability of housing, see Fig. 1-2.

1.2.3 Private Market

In addition to the public resale market, there is a small, but growing private housing market. Private housing is available only to the wealthiest of Singaporeans and non-residents, however, gains in equity through growth in the public market have allowed many upwardly mobile residents to make the jump from public to private housing. As in the public sector, the private residential market is tightly controlled by the government. The supply of new units is directly regulated through Government Land Sales (GLS) and a multi-step approval process, and demand is controlled through financing terms and policies on the subleasing of HDB units.

1.3 Understanding the Past and Preparing for the Future

This study considers land as a limited resource, one that has enabled Singapore's rapid development, but could limit its future growth. Residential land is the focus because it represents one of the primary land use types in Singapore, and it is most closely tied to the changing population. Two measures, residential land use footprint and mean time to redevelop, are used to quantify the effects of housing development and policy on land use.

Singapore's attitude towards urban planning has historically been proactive, and very long-sighted. Early decisions to build at high densities, especially in the residential sector, have resulted in a very efficient use of land resources and the maintenance of considerable undeveloped and recreational space on the island. The first part of this study looks at the factors that drive land use footprint and redevelopment potential, and examines how planning decisions have affected the past, present, and future of land use in Singapore.

While planning decisions are the dominant influence on long-term land use trends, instability in residential markets can contribute to significant short-term fluctuations in resource demand measures. Even though Singapore's housing markets are more actively regulated than many other countries', they are not immune to short-term volatility. Currently, both Singapore's public resale and private market prices are on the rise. While the private market growth has begun to slow, signs point to a "bubble" in the public resale market that may soon burst. A suite of new policies have been implemented over the last year and should begin to take hold of the market shortly. How they effect the value of properties as well as the long-term residential land use is yet to be seen.

The second part of this study seeks to understand the relationship between housing market fluctuations and changes in the housing stock. In order to assess the market and resource implications of housing policy scenarios, a System Dynamics model is developed to simulate Singapore's unique housing market dynamics.

Given the government's role in provision of public housing, and its tight regulation of the public resale and private markets, policy has a direct effect on every aspect of the residential landscape. This study seeks to evaluate how various residential planning and housing policy strategies could affect market swings, land use, and the flexibility of future growth.

Chapter 2

Background

Providing for an exploding global urban population is at the forefront of many developing cities' planning and policy agendas. Current trends suggest that the battle for long-term sustainable development will be waged at the city scale, rather than the national level [19]. As the primary centers of trade, production, and consumption, cities serve as major markets for the exchange of human and physical capital [20].

At its simplest abstraction, the function of a city is to provide the resources, infrastructure, and markets for its citizens to survive—ideally, to thrive. The degree to which citizens are thriving can loosely be understood as quality of life, and is influenced by many parameters. One of the key components in a city that greatly affects the quality of life for its occupants is the provision of housing.

Edward Glaeser's *Triumph of the City* extolls the virtues of cities, particularly the ability of urban density to bring human, economic, and physical capital together, increasing efficiency and generating innovation [2]. He also acknowledges the need for cities to provide for ever-larger populations in order to take full advantage of density-derived benefits. Housing, and plenty of it, is a key ingredient in the recipe of a productive, growing city. Yet, with more housing comes more demand for urban land, which is often in limited supply. Ultimately, Glaeser's thesis is a plea for higher density residential accommodations in thriving cities. Working from his viewpoint, the study presented here investigates the relationships of a city's population, housing stock, and land resources.

2.1 Industrial Ecology

For the path to a sustainable resource future to be laid, a reliable quantitative approach for evaluating the resource implications of planning and policy scenarios is required. To study the city in a rigorous manner, a framework has been established for understanding the components of human driven systems, their interrelationships, and their interactions with the surrounding environment. In the latter half of the last century, the field of Industrial Ecology emerged to formalize the way in which anthropogenic systems can be understood in a manner similar to natural ecosystems. Generally, as Erkman states, "the industrial system can be seen as a certain kind of ecosystem" [21]. Industrial Ecology is defined by three key attributes:

> 1. *It is a systemic, comprehensive, integrated view of all the components of the industrial economy and their relations with the biosphere.*
> 2. *It emphasizes the biophysical substratum of human activities, i.e. the complex patterns of material flows within and outside the industrial system, in contrast with current approaches which mostly consider the economy in terms of abstract monetary units, or alternative energy flows.*
> 3. *It considers technological dynamics, i.e. the long term evolution (technological trajectories) of clusters of key technologies as a crucial (but not exclusive) element for the transition from the actual unsustainable industrial system to a viable industrial ecosystem.* [21]

Within the larger context of Industrial Ecology is the sub-field of Industrial Metabolism, pioneered by Ayres [22], and comprising "the whole of the materials and energy flows going through the industrial system. It is studied through an essentially analytical and descriptive approach (basically an application of materials-balance principle), aimed at understanding the circulation of materials and energy flows linked to human activity..." [21]. When applied specifically to a city, the same principle is called Urban Metabolism.

2.2 Urban Metabolism

In 1965, Abel Wolman published "The Metabolism of Cities" in *Scientific American*, which examined the inflows, outflows, and changes to the stocks of a hypothetical American city of one million inhabitants [23]. Although not the first reference to an Urban Metabolism, Wolman's study was seminal in carrying-out a broad account of the metabolic activities of a city as a parallel to an organism's metabolic process, taking into account consumption (inflows), digestion (processing and changes to stock), and excretion (outflows). Within the broader field of Industrial Ecology, Urban Metabolism studies the resource consumption, transformation, storage, and excretion of urban areas. Specific methodologies for conducting Urban Metabolism studies have been catalogued by Daniels [24, 25] and Niza, et al. [26]. Dedicated Urban Metabolism studies have been carried out for several cities [27], and at a global scale [28]. Over the last several years, Niels Schulz has undertaken an in-depth study of the metabolism of Singapore [29, 30], which currently serves as the benchmark for understanding Singapore's physical economy, and motivated much of the interest for this study.

The important distinction between Urban Metabolism and other urban analysis methodologies is the focus on physical materials, rather than economic units. While monetary values fluctuate—inflate, deflate, depreciate, etc.—physical units remain constant over time, and permit more relevant resource studies than their economy-based counterparts. The most widely accepted methodology for this type of tracking physical resources is called Material Flow Accounting (MFA) [31].

2.3 Material Flow Accounting

Marina Fischer-Kowalski gives a comprehensive history of the study of *metabolism* from its biological roots in the mid-1800s to present urban applications, and the resulting development of MFA to serve as a method for physical analysis [32, 33]. MFA has since been standardized as a methodology for economy-wide physical accounts by Eurostat, the statistical branch of the European Commission [34]. Generally, "economy-wide material flow accounts and balances show the amounts of physical inputs into an economy, material accumulation in the economy and outputs to other economies or back to nature," see Figure 2-1.

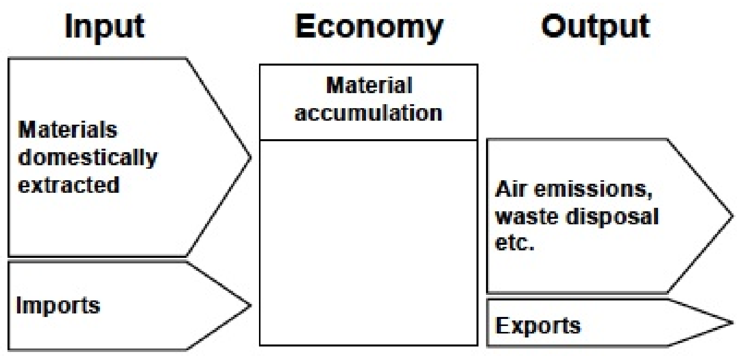

Figure 2-1: Scope of economy-wide material flow accounts [34]

The results from MFA are a series of indicators useful in comparing the resource efficiency of various economies, as well as being relevant to current policy-making. Recent studies have used Material Flow Accounting as a means to quantify the relationship between the growth of economies and the change in physical resource demands and environmental impacts [35]. The connection between economic and physical flows is stressed in Emily Matthews', *The Weight of Nations: Material Outflows from Industrial Economies* [36], a reference to Adam Smith's foundational economics text, *The Wealth of Nations* [37].

Recently, MFA has been expanded to quantify the impacts of the built environment, in addition to industrial-economic processes. John Fernández looks specifically at the resource intensity of buildings in China [38], while David Quinn considers the material consequences of rebuilding New Orleans' residential sector after hurricane Katrina [39], and Karen Noiva assess the resilience of Singapore's water storage and delivery infrastructure using a material flow accounting framework [40].

Material Flow Accounts of entire cities, like London [41], are being used to generate ecological footprints—a method for relating environmental impacts to spatial land demands. Resource footprints are described in Section 2.4. Singapore's static, annual

Material Flow Accounts have also been gathered by Schulz [42], giving a time-series snapshot of the island's material inputs and outputs between 1962 and 2002, see Figure 2-2.

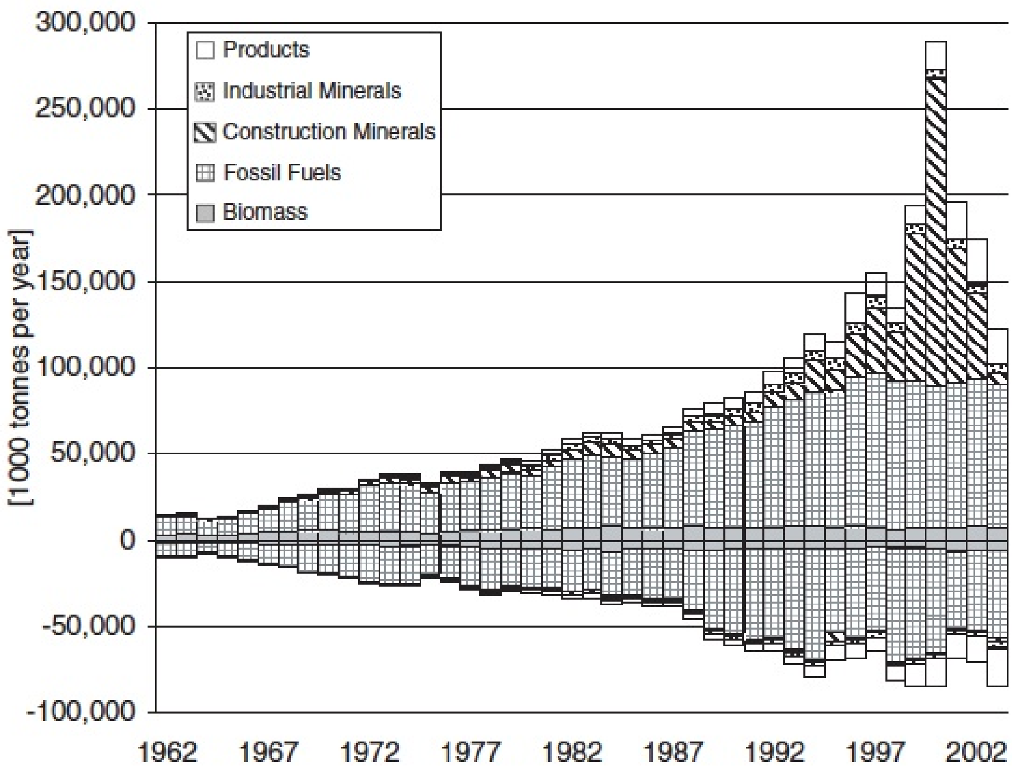

Figure 2-2: Singapore import and export, physical flows, 1962–2002 [42]

However, for MFA to have a significant effect on future policy determination, static material flow accounts must be extended from mere data collection exercises. The underlying mechanisms driving material demands must be identified, understood, and modeled. Using these functional models, projections about future material flows can be made and the influence of proposed policies can be evaluated. Several such dynamic MFA studies have been proposed and carried out in the recent past.

In 2006, Müller proposed a dynamic stock and flow model for continuous accounting of housing construction material flows in the Netherlands [43]. The next year, Bergsdal, Brattebø, and Bohne joined Müller to adapt the dynamic model to housing in Norway [44]. In 2010, Mingming Hu again adapted the Müller model to assess construction material and demolition waste flows in Beijing [45]. And as a precursor to this study, a similar methodology was proposed to extend Schulz' work by dynamically modeling Singapore's resource flows [46]. Ultimately, for this study residential land was chosen over construction material as the most important resource measure for the viability of future development. Chapter 3 details the adaptation of Müller's model from dynamic construction material flow accounting to residential land flow accounting.

2.4 Resource Footprints

For policy-makers to act on information provided by scientific investigation, the information must meet two criteria: it must be collected, analyzed and calculated in a repeatable manner; and the information must be distilled to a simple, relevant form that is readily understood and actionable. As emphasized by Selin and Eckley, scientific information must be *salient* to the decision makers who will use it to inform policy [47].

One common method researchers have used to increase saliency is the formation of indicator measures. When describing resource requirements, there are two distinct classes of indicators: intensity measures, and resource footprints.

Intensity measures normalize resource use against a unit of service delivered. For example, in the material flow accounting sphere, Material Intensity per unit Service (MIPS) might represent the material required to deliver one housing unit, or one passenger-kilometer of vehicle travel [48]. In this case the housing unit or passenger-kilometer traveled are functional units of service.

In contrast, resource footprints, pioneered by Wackernagel and Rees, relate resource requirements to the land area needed to support a unit of service [49]. The foundational footprint indicator is the ecological footprint. Reported by the Global Footprint Network, it quantifies the resource requirements of nations in terms of the global land area necessary to deliver those resources [50]. Because of the complexity associated with accounting for different land types and a broad distribution of delivered ecosystem services, the ecological footprint concept has received criticism as an oversimplified resource measure [51]. However, work is ongoing to improve the relevance of the ecological footprint methodology [52], and techniques are being developed to more closely integrate material flow accounting and ecological footprinting [53].

Despite valid criticism and recognized shortcomings, the ecological footprint remains a viable and popular method for characterizing the resource requirements of anthropogenic systems. Because the footprinting method presents the abstract, and often inaccessible, concept of diverse resource requirements in terms of land area, which is readily understood by nearly any audience, it the best available resource indicator for universal saliency.

For this study, a new footprint measure is introduced, Residential Land Use Footprint, defined in Subsection 3.1.1. Residential land use footprint represents the residential land area required to house one occupant. This measure allows residential land use comparisons across a variety of housing typologies, family-structures, and building densities. By aggregating four fundamental influencing factors, which are described in detail in Chapter 3, the footprint makes salient comparisons of residential land use possible. The indicator is relevant for tracking changes in residential land use in one city over time, as well as making inter-city comparisons.

2.5 System Dynamics Modeling

As described in Section 2.3, the transition from static to dynamic material flow accounts is a necessary step in fully understanding and projecting resource requirements into the future. In order to move from static accounts to dynamic simulation, System Dynamics modeling is utilized. The direct connection between MFA and System Dynamics is their shared focus on stocks and flows. In MFA stocks and flows are recorded from annual or quarterly data, where in System Dynamics flow rates are generated endogenously, and stocks are updated according to the accumulation of inflows and outflows. In this way, the causal influences of various flow rates are an inherent component of a comprehensive System Dynamics model, where MFA is merely a cause-agnostic accounting exercise.

Although not specifically identified as such, the Müller model of dynamic material flow accounting is effectively a simple System Dynamics model. It utilizes exogenous population inflows and outflows in conjunction with time dependent parameters—lifestyle, and material intensity—to drive the inflows and outflows of the unit and material stocks.

Beyond dynamic simulation of stocks-and-flows, as shown in the Müller model and the adapted version in Chapter 3, System Dynamics also allows for the incorporation of feedback loops, producing a more comprehensive system-wide model, like the one presented in Chapter 6.

2.5.1 History

Building on his experience with control theory—utilizing feedback in the control of electro-mechanical systems—and enabled by recent advancements in computation, Jay Forrester developed a means for simulating complex feedback-driven systems in the late 1950s at MIT [54]. As a professor in the Sloan School of Managment, he first applied the modeling technique to the management of industrial production systems, publishing *Industrial Dynamics* in 1961, formally defining the field of System Dynamics [55].

In short order, System Dynamics was put to use studying urban issues. Working with former Boston mayor, John F. Collins, Forrester published *Urban Dynamics* in 1969, which simulated the process of urban decay as the result of interactions between the population, urban economy, employment, and housing policy [56]. Although its results were contentious, and perhaps insensitive to the urban poor, the demonstration of quantitative urban evaluation represented a significant advance in the study of cities [57]. In fact, Richardson discusses in detail the apparent relevance of the study to Singapore's urban development strategy in it's first 50 years of independence [58].

Shortly thereafter, Forrester was famously commissioned by the Club of Rome to develop a model of worldwide population, economy, resource, and pollution dynamics. The result, *World Dynamics*, which was conceptualized by Forrester on his trans-

Atlantic flight home, was published in 1971 and served as the basis for the Meadows' seminal study, *The Limits to Growth* [59, 60].

System Dynamics is a method of modeling causal relationships between like and unlike variables using stock-and-flow structures and feedback loops. Mathematically, System Dynamics uses differential equations and numerical integration to calculate auxiliary variables, derive flow rates and accumulate flows in stocks, all with respect to time. Unlike other simulation modeling techniques, feedback is inherent to the System Dynamics modeling framework, and a graphic language of model representation is used to visualize and explain the mathematical structure [61]. The basic structural elements, and their graphic representations are outlined below, and can be combined in a variety of ways to form specific behavioral structures [62].

2.5.2 Causal Loops

Causal loop diagramming is the first step in formulating a System Dynamics model. The process begins by listing important variables, and drawing causal connections between them, see Figure 2-3. In this phase, all variables are shown as auxiliary variables represented merely by their names. Causal links are shown as curved arrows, with a polarity denoting the direction of influence when all other variables are held constant.

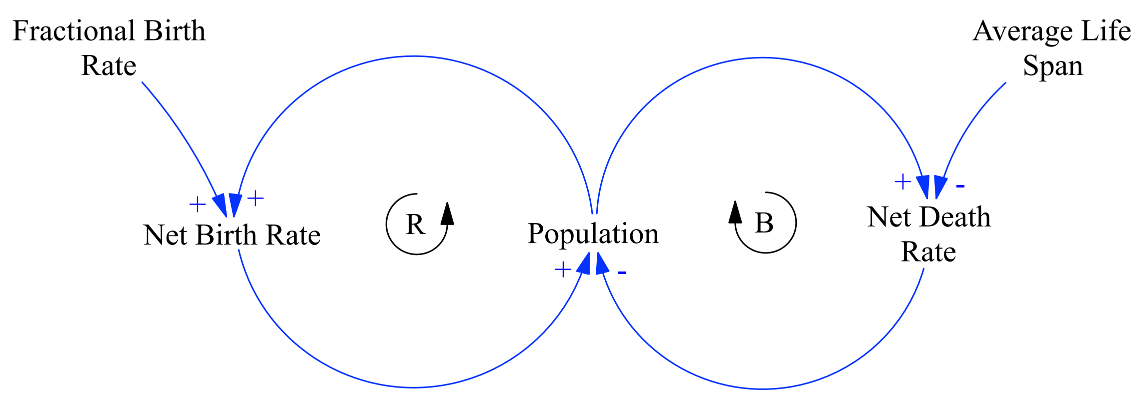

Figure 2-3: System Dynamics causal loop diagram: feedback loops

For instance, in Figure 2-3, the lower left causal link can be read as, "holding all else constant, an increase in net birth rate causes an increase in population," and the converse is true. Causality is exceptionally important in System Dynamics modeling, and much effort is devoted to detailing relationships between variables in functional terms to ensure that the statement made by the causal link is universally true. Accordingly, dimensional consistency is required among all causal relationships.

When a series of causal links returns to the original variable, a feedback loop is closed. The polarity of that loop forms a key behavioral element of the model, and is denoted by a circular arrow in the center of the loop. If the polarity is labeled 'R', it is a reinforcing loop, in which an increase in one variable of the loop results in a further increase in that variable after tracing around the loop. If an increase in one variable results in its decrease after tracing around the loop, that feedback loop has a balancing effect, and is denoted with a 'B'.

In Figure 2-3, the reinforcing loop on the left can be read as, "an increase in population causes the net birth rate to increase, which further increases population." Reinforcing feedback is the fundamental structure that generates exponential growth and decay, and is detailed in Subsection 2.5.5. Similarly, the balancing loop on the right is read as, "an increase in population causes the net death rate to increase, which decreases the population." In this way the loop has a balancing, or moderating effect on the population.

2.5.3 Stocks and Flows

The next step in defining a System Dynamics model is to trace the flow and accumulation of information and materials through the use of stocks and flows. Certain variables in the model, such as constant parameters or unit conversion factors, are not related to the stock-and-flow structures. These variables are called auxiliary variables and are denoted only by their names. Stock variables, which accumulate inflows and outflows of information or physical assets are denoted by a box around the variable name. A stock is increased by its inflows and decreased by its outflows. Flow variables are denoted by a *valve* symbol above their name, and moderate the flow rate through *pipes* linking stocks to other stocks, sources, or sinks. Sources and sinks, denoted by cloud symbols, are outside the boundaries of the model and are assumed to be infinite in scale.

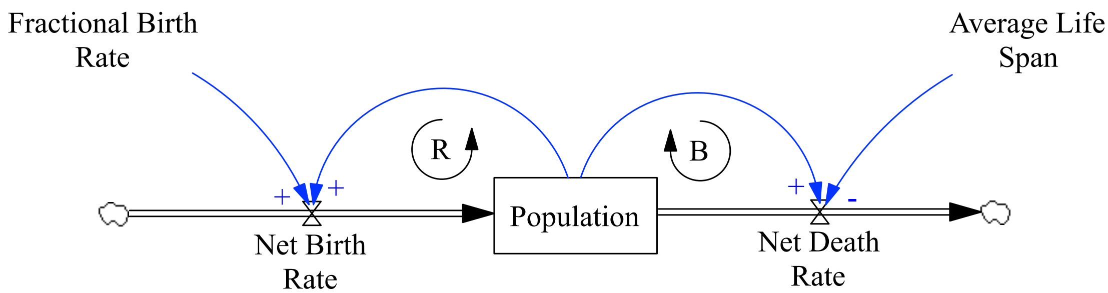

Figure 2-4: System Dynamics stock and flow structure: inflow and outflow

In Figure 2-4, Fractional Birth Rate and Average Life Span are auxiliary variables. Population is a stock variable increased by Net Birth Rate inflow, and decreased by Net Death Rate outflow. Despite the specification of variable types, the function of the causal loops remain the same.

2.5.4 Table Functions

Frequently as a model grows in complexity, and begins to incorporate both physical and informational flows, dimensionally dissimilar and non-linear relationships will need to be modeled. For instance, in the running population example, Figure 2-5 shows an additional balancing loop that reduces the Average Life Span as the population increases beyond its sustainable level.

The loop relates the population, measured in *people*, to average life span, measured in *years*. This connection is not dimensionally consistent, nor is it described by a simple, linear equation. However, there is certainly a direct effect of overpopulation on decreasing lifespan. So, to relate these two unlike variables, System Dynamics employs a table function, which allows elastic, non-linear relationships to be defined and modified graphically.

In order to maintain dimensional consistency, the population is normalized by the sustainable population—a constant "normal" population level. The resulting

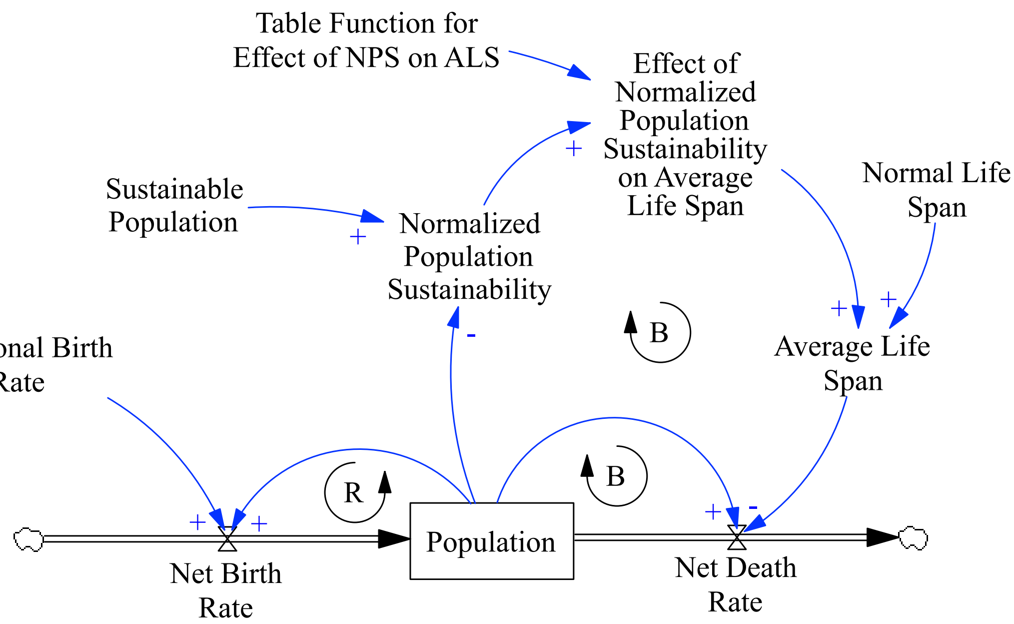

Figure 2-5: System Dynamics structure for defining non-linear relationships between variables of different units: table function

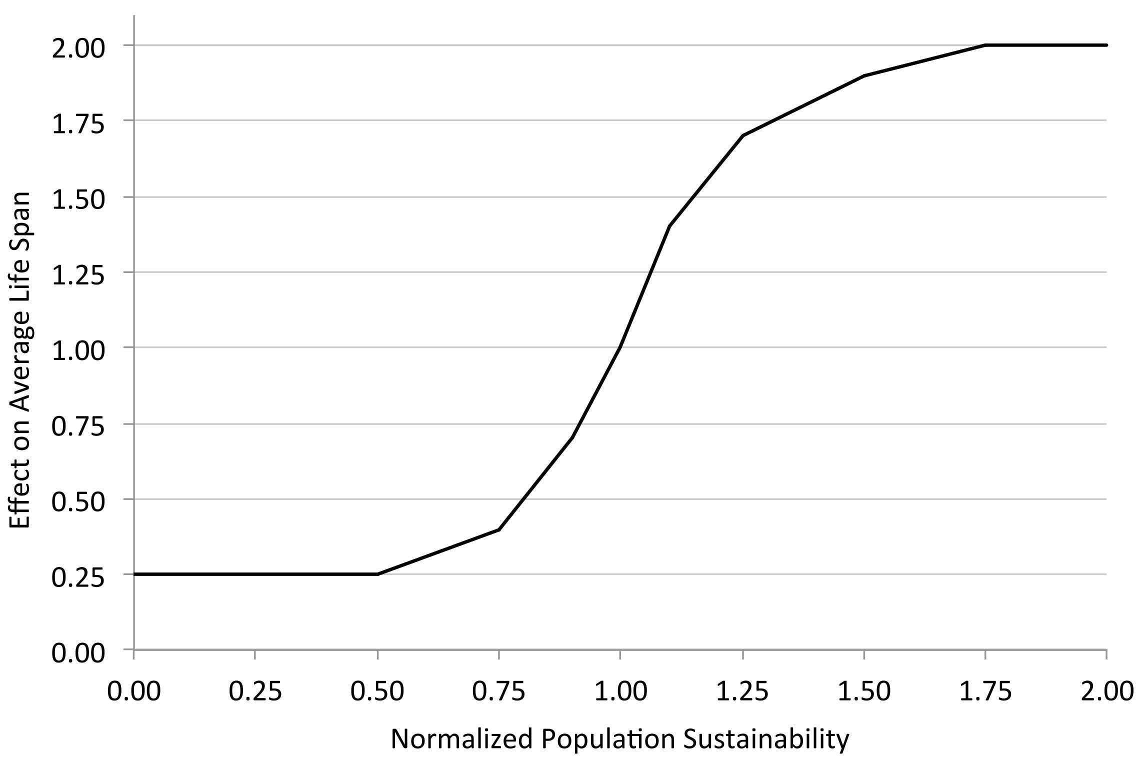

Figure 2-6: Table function for the effect of normalized population sustainability on average life span

normalized population sustainability is a dimensionless quantity, where a value of 1 represents exactly the sustainable population, a sustainability value less than 1 represents a population that exceeds the sustainable level, and a sustainability value greater than 1 represents a population below the sustainable population limit. The normalized population sustainability is the independent input to the table function, and is plotted on the X-axis. The resulting effect on the average life span is the dependent output of the table function and is plotted on the Y-axis. An example table function for this relationship is shown in Figure 2-6.

To properly calibrate the System Dynamics model, data for the input and output elements—population and average life span—should be gathered and used to fine-tune the table function.

2.5.5 Mathematical Behavior: Exponential Growth

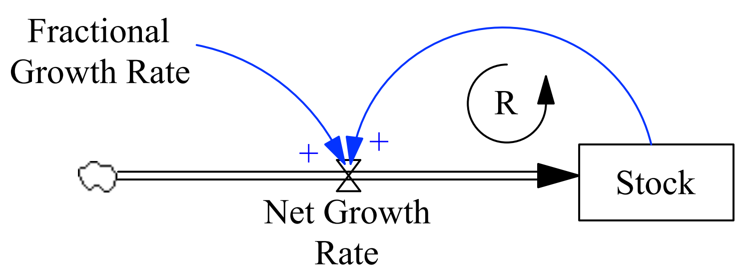

Figure 2-7: General feedback structure for exponential growth

The last step in model formation is to define the equations and units for each variable in the model. For this description, a generalized subset of the example model is defined and evaluated, mathematically. The structure is a simple inflow increasing a stock, see Figure 2-7.

The stock, S, accumulates the inflow—net growth rate, NGR:

$$S(t) = S(0) + \int NGR \, dt \tag{2.1}$$

In this case the net growth rate ($units/year$) is the product of the level of the stock, S ($units$) and the fractional growth rate, g ($\%/year$):

$$NGR = Sg \tag{2.2}$$

When evaluated, the resulting behavior generated by the reinforcing feedback loop is exponential growth of the stock, S. The following description derives the behavior of the stock, mathematically. In each time step the level of the stock changes by the value of the inflow:

$$\frac{dS}{dt} = NGR \tag{2.3}$$

Combining Equations 2.2 and 2.3 gives:

$$\frac{dS}{dt} = Sg \tag{2.4}$$

Rearranging the terms gives:

$$\frac{dS}{S} = g \, dt \tag{2.5}$$

Both sides are integrated:

$$\int \frac{dS}{S} = \int g \, dt \tag{2.6}$$

Giving:

$$\ln(S) = gt + c \tag{2.7}$$

Taking exponentials of both sides gives:

$$S(t) = c^* \exp(gt) \tag{2.8}$$

Where:

$$c^* = \exp(c) = S(0) \tag{2.9}$$

So, finally:

$$S(t) = S(0)\, e^{gt} \tag{2.10}$$

Given the complexity of generating a closed-form solution for a single stock with only a single inflow, it becomes clear that hand calculation of a large model would not be possible. Therefore, for this study the dedicated System Dynamics software platform, VenSim, is used for all modeling. Documentation of the models can be found in Appendixes A-E.

Chapter 3

Planning & Residential Land Use: Methodology

In order to analyze the efficiency of residential land use in Singapore, relevant measures by which land use can be quantified must be defined. Calculating these measures at a single point in time, for instance the present state of development, is of use for comparing Singapore to other cities. But, it is equally important to consider how these measures have varied over time to understand the trajectory of residential land use, what parameters affect its course, and where it may be headed in the future.

3.1 Residential Land Use Measures

Two measures are proposed as relevant indicators of the current and future states of residential land use in a land-constrained city like Singapore.

Residential land use footprint, Λ_r, measures the total residential land required by each inhabitant of the city. Lower values represent greater residential space efficiency and either allow for a larger population, or leave more non-residential land for other uses. The concept of 'footprinting' was introduced by Wackernagel and Rees [49] as a means to quantify the ecological impacts of a society on nature by calculating the land area necessary to support its human activity. In Singapore, where high-rise living is the standard and most residents have no land or yard of their own to speak of, land use footprint considers the impact of residential activity in terms of the area of land required to support housing for a single occupant.

Mean residential redevelopment time, T_r, is a relative measure of the average time required for government initiated redevelopment of a plot of residential land. Shorter redevelopment time means more freedom for the government to relocate housing and redevelop residential land to better suit future demands.

3.1.1 Residential Land Use Footprint

Residential land use footprint, Λ_r, measures the per capita residential land use in $m^2/person$. As an aggregate value for the whole city, it is calculated as:

$$\Lambda_r = \frac{LA_r}{P_{total}} \tag{3.1}$$

where LA_r is the total residential land area in m^2, and P_{total} is the total population. This formulation permits simple calculation of the total residential land use footprint using only the current residential land area and current population.

While Equation 3.1 gives a single aggregate city-wide value, to calculate the footprint for a smaller area such as a single building the following equation is more suitable:

$$\Lambda_r = \frac{NFA \times GF}{PR \times \rho_{occ}} \tag{3.2}$$

Equation 3.2 highlights the relationship of the four primary factors that influence land use footprint:

Net Floor Area per Unit: NFA , $net\, m^2\, floor/unit$

average net floor area per unit, see Subsection 3.3.1

Grossing Factor: GF , $gross\, m^2\, floor/net\, m^2\, floor$

ratio of gross floor area to net floor area, see Subsection 3.3.3

Plot Ratio: PR , $gross\, m^2\, floor/m^2\, site$

ratio of gross floor area to site area, see Subsection 3.3.2

Occupant Density: ρ_{occ} , *occupants/unit*

average number of occupants per unit, see Chapters 6–8

As shown, land use footprint is directly proportional to the net floor area per unit and the grossing factor; all else equal, larger units and units with higher grossing factor result in a larger footprint. Plot ratio and occupant density are inversely proportional to the land use footprint. Higher plot ratio and occupant density lead to a smaller footprint.

3.1.2 Mean Residential Redevelopment Time

Given Singapore's changing population, household makeup, and distribution of wealth, the housing stock is far from a static entity. It must dynamically react to the demands of the population, and to the limitations imposed by housing policy and long-term planning. The ability to alter current land use trends through redevelopment is critical to the future of residential land planning. Mean residential redevelopment time, T_r, is an indicator of how quickly a typical parcel of the current residential land stock could be redeveloped. T_r is measured in years and varies between 5.0—a completely flexible scenario, in which all residential land is undeveloped and immediately available for redevelopment—and 20.0—the completely rigid private development of all available residential land. Mean residential redevelopment time is a weighted average of redevelopment times for each major residential land use type, calculated as:

$$T_r = (\tau_u \times \phi_u) + (\tau_{pub} \times \phi_{pub}) + (\tau_{priv} \times \phi_{priv}) \tag{3.3}$$

where ϕ_u, ϕ_{pub}, and ϕ_{priv} are the fractions of undeveloped residential, public residential, and private residential land area, such that:

$$\phi_u + \phi_{pub} + \phi_{priv} = 1 \tag{3.4}$$

Any of the land use fractions can be calculated using the known land areas—LA_u, LA_{pub}, LA_{priv}—and the total residential land area allotment, LA_{allot}, using the following equations:

$$LA_u + LA_{pub} + LA_{priv} = LA_{allot} \tag{3.5}$$

$$\phi_x = \frac{LA_x}{LA_{allot}} \tag{3.6}$$

And τ_u, τ_{pub}, and τ_{priv} are redevelopment time, in years, for undeveloped residential, public residential and private residential land, respectively. Redevelopment times are the average time it takes to redevelop a plot of the given land type. See Table 3.1 for the tabulation of redevelopment times used in this study of Singapore.

Table 3.1: Land use redevelopment times

Land Use	**Redevelop Time,** τ_x *years*
Undeveloped Residential, u	5
Public Residential, *pub*	10
Private Residential, *priv*	20

Based on dialogue with a planner at the URA, a time period of 4 to 5 years was given for high rise development of previously undeveloped residential land. This is the time between the government land sale and the first occupants moving into the completed building. Because a planning period is needed to determine which land plots to sell, as well as several months for developers to bid, the long end of the range, 5 years, was chosen for the 're'-development time of undeveloped land.

For public residential land, the Selective En Bloc Redevelopment Scheme (SERS) is used to relocate occupants to newer developments and then demolish and redevelop aging public housing developments [63]. Based on the SERS data, it takes approximately 5 years between the announcement of a new SERS site and the relocation of all residents to new replacement flats. Only after the relocation is complete can the old units be demolished and redeveloped, taking another 5 years. So the total time to redevelop is 10 years.

Finally, for private residential redevelopment an estimation was made based on the following assumptions and logic. For most private land, the maximum time to redevelopment is 99 years, based on the standard land lease term. A typical plot in a set of uniformly distributed private landed properties would then have an expected remaining lease time equal to the mean, or roughly 50 years. The URA, however, does have the power of eminent domain over private properties in the interest of redevelopment, so this time could be decreased in the interest of better long term residential land use, but certainly not as quickly as public housing. For this reason the value of 20 years, between the 10 year minimum and 50 year average, was chosen. Many arguments could be made for other values, and further study should be devoted to calculating this redevelopment time more specifically. For the time being, 20 years is considered a starting estimate.

3.2 Modeling Framework

Section 3.1 presented the static calculations for determining land use footprint and mean redevelopment time at a given moment. In this section, a framework is described for simulating land use footprint and mean redevelopment time continuously. The structure is adapted from the stock-and-flow model of the Netherlands' and Norway's housing stock by Müller, et al., see Figure 3-1 [43, 44].

Müller's model, although represented in a different graphic style than the previous System Dynamics description, utilizes the same type of stock (rectangle) and flow (oval) variables. The stock-flow chains are arranged in a co-flow structure [64], in which the three stocks track three different properties of the same housing stock: population housed, number of units, and tons of materials in use. The hexagonal variables are time-dependent parameters that influence the occupant density (lifestyle) and material intensity of new units being added to the stock, as well as the rate at which units and materials are demolished (lifetime). While Müller's model simulates construction material use over time, a simple adaptation of the model substitutes land use for construction materials.

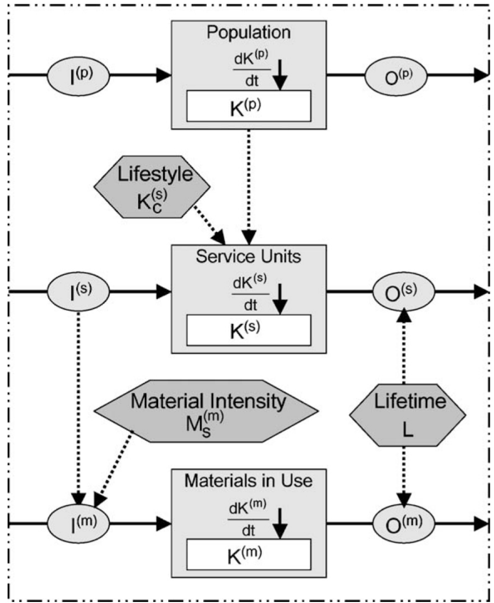

Figure 3-1: Netherlands housing stock-and-flow model with co-flows [43]

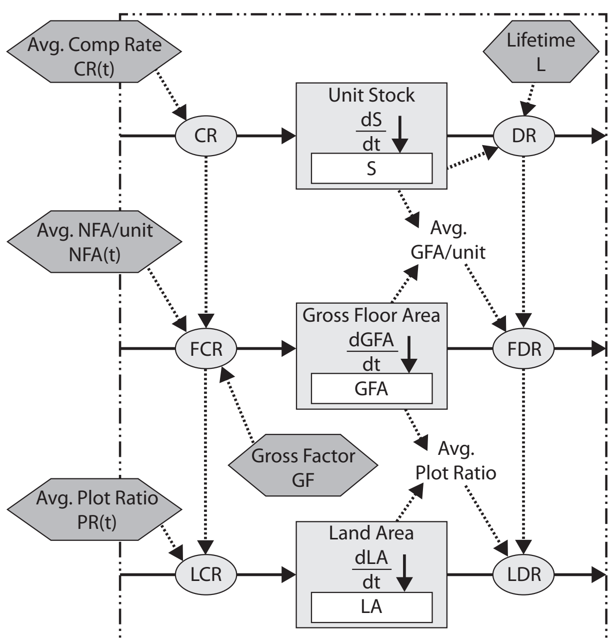

Figure 3-2: Singapore residential land stock-and-flow model with co-flows

The model in Figure 3-2 uses the same co-flow structure as Müller's, however, it tracks a different set of housing stock properties: number of units, gross floor area of all units, and land area occupied by all units. New unit completions, $CR(t)$, are input exogenously into the completion rate, CR, which increases the unit stock, S:

$$CR = CR(t) \tag{3.7}$$

The unit stock is reduced by the outflow of unit demolitions, DR, which is a function of the current stock, S, and the unit service lifetime, L:

$$DR = \frac{S}{L} \tag{3.8}$$

The unit stock accumulates, or integrates, the difference between the inflow and outflow at each time step:

$$\frac{dS}{dt} = CR - DR \tag{3.9}$$

$$S = S_{init} + \int (CR - DR)\, dt \tag{3.10}$$

$$\tag{3.11}$$

In a co-flow structure each set of flows is used to drive the next, parallel set of flows through conversion factors. The new floor area completion rate, FCR, is a function of the completion rate, CR, the average net floor area per unit, $NFA(t)$, and the grossing factor, GF, which converts net to gross floor area. The floor area demolition rate outflow, FDR, is driven by the unit demolition rate, DR, and the average gross floor area per unit, which is calculated using the current gross floor area stock and the unit stock. Again, the gross floor area stock, GFA, is the accumulation of the inflow, less the outflow:

$$FCR = CR \times NFA(t) \times GF \tag{3.12}$$

$$FDR = DR \times Avg.\,GFA\,per\,unit \tag{3.13}$$

$$Avg.\,GFA\,per\,unit = \frac{GFA}{S} \tag{3.14}$$

$$\frac{dGFA}{dt} = FCR - FDR \tag{3.15}$$

$$GFA = GFA_{init} + \int (FCR - FDR)\,dt \tag{3.16}$$

The final land area co-flow is structured in the same way, but is driven by the gross floor area flows. The land area completion rate, LCR, is a function of the floor area completion rate, FCR, and the average plot ratio, $PR(t)$. The land area demolition rate outflow, LDR, is driven by the floor area demolition rate, FDR, and the average plot ratio, which is calculated using the current gross floor area stock and land area. The land area stock, LA, is the accumulation of the inflow, less the outflow:

$$LCR = \frac{FCR}{PR(t)} \tag{3.17}$$

$$LDR = \frac{FDR}{Avg.\,Plot\,Ratio} \tag{3.18}$$

$$Avg.\,Plot\,Ratio = \frac{GFA}{LA} \tag{3.19}$$

$$\frac{dLA}{dt} = LCR - LDR \tag{3.20}$$

$$LA = LA_{init} + \int (LCR - LDR)\,dt \tag{3.21}$$

This model uses five exogenous input parameters: the average unit completion rate, $CR(t)$; average net floor area per unit, $NFA(t)$; average plot ratio, $PR(t)$; housing unit lifetime, L; and grossing factor, GF. Occupant density, ρ_{occ}, is not included in this stage of the model, but is addressed in Chapters 6–8, which deal with housing markets, price, and population behavior.

To calculate the land use footprint and mean redevelopment time, the model structure shown in Figure 3-2 is repeated for each of the three primary housing types: public, private landed, and private non-landed. These three sub-models produce the total land area for each of the three residential zoning types. When summed and divided by the total population at the given time step, per Equation 3.1, the land use footprint is calculated at each time step over the modeled time period. Additionally, the three land area stocks, the total residential land area allotment, and the residential redevelopment times combine, as in Equations 3.3–3.6, to produce the mean residential redevelopment time at each time step.

A variety of data sources were analyzed to determine the various static and time-dependent input parameter values for this modeling exercise. Section 3.3 describes the data used to calibrate and drive the model.

3.3 Historical and Reference Data

The Singapore Yearbook of Statistics records annual data for the completion rate of new units, stock of units in service, and demolition rate of existing units [14] for public, private landed, and private non-landed housing. From this data, the initial value for the unit stock, S, and the time dependent values for average unit completion rate, $CR(t)$, and lifetime, L, are determined for each of the three housing types. For reference, the completion rate data is shown in Figure 3-3.

Because most of the housing stock in Singapore is quite new, the average demolition rate over the period of interest is much lower than would be expected in the long-term equilibrium condition. In order to calculate an appropriate unit lifetime, the actual stock is divided by the actual demolition rate for each year, resulting in an average unit lifetime at each time step. Since no visible trend is evident in the lifetime of private landed or non-landed units, the annual values over the modeled period, 1990–2011, are averaged and the result—150 years—is used as a constant parameter for unit lifetime.

For public housing, no continuous trend in lifetime is observed, however there is

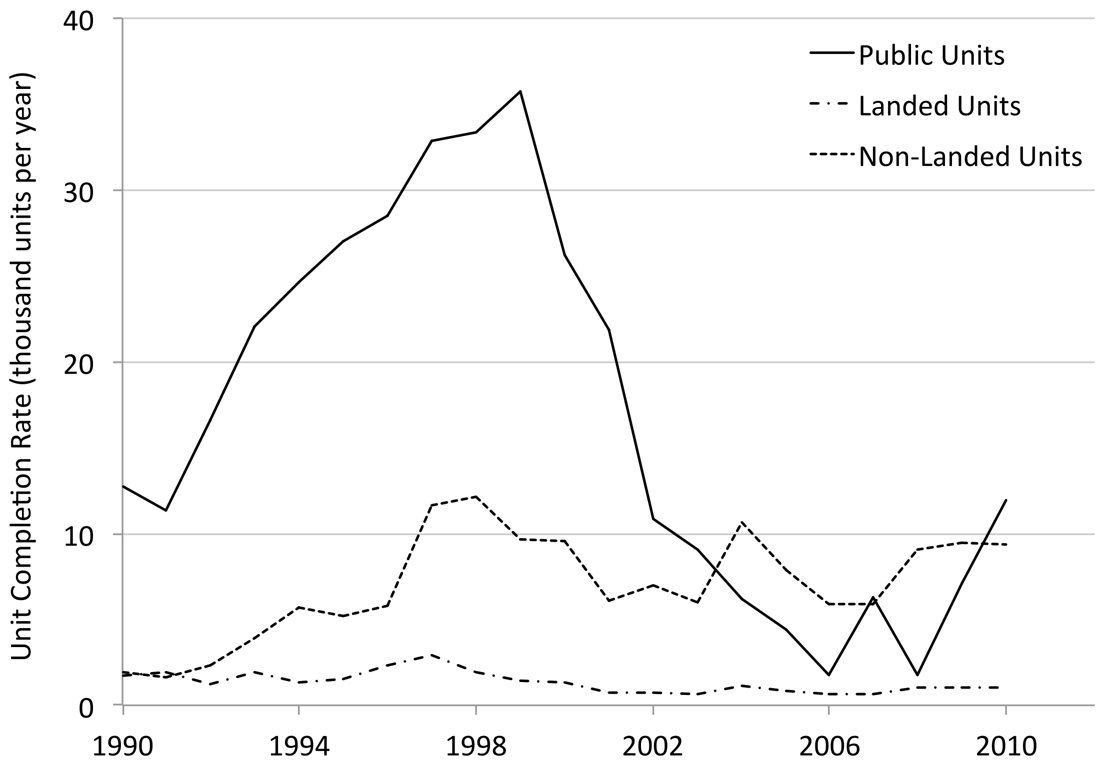

Figure 3-3: New unit completion rate, 1990–2011

a distinct decrease in the demolition rate after 2000. The same 150 year lifetime is observed between 1990 and 2000, but as the completion rate of new public units falls dramatically after 2000, so too does the demolition rate. From 2000–2011 the service lifetime steps up to 500 years, or 0.2% of the stock demolished per year.

To verify the accuracy of the calculated unit lifetimes, the unit stock was simulated using the exogenous unit completion input, $CR(t)$, and the calculated lifetimes, $L(t)$. The simulated stock, S, was compared to the actual recorded stock data over the modeled period to verify that the two stock behaviors were reasonably similar. Using the values discussed above all three unit stocks—public, private landed, private non-landed—were simulated quite accurately.

3.3.1 Net Floor Area per Unit

The trend in net floor area per unit has a direct effect on the residential land use footprint, and is influenced primarily by the population's desire for space and ability to afford that space. Housing suppliers, in return, provide units that they believe will satisfy demand as well as remaining affordable enough to sell quickly. Thus it is worthwhile to consider the magnitude and trend in physical house size to gain insight into how efficiently residential floor area has been used, and how that is likely to change in the future. The average net floor areas of each unit type are recorded in Tables 3.4 & 3.5.

Consider, first, the private housing sector in Singapore. Landed housing sits at the top of the price pyramid and units are quite large by any living standard—detached houses average about 600 gross square meters in floor area, while typical terrace houses are roughly half the size. A visual survey of landed housing in Singapore suggests that the size and density of landed housing has remained relatively constant for the last several decades. The data for average landed housing floor area comes from the URA's database of private residential property transactions with caveats lodged [65]. This database does not contain information on when units were constructed, so no further information is available on the trends of private landed unit size over time. Also remaining constant is the relative distribution of new landed units, which maintains its historical average of roughly 10% detached, 30% semi-detached, and 60% terrace housing, see Table 3.2.

Residing above public housing but below landed housing in price are the private non-landed housing units: apartments and condominiums. Much smaller than landed units, a typical Singapore apartment measures 99 net square meters, while an average condominium encloses 124 square meters of net floor area. The private non-landed floor area data comes from the same property transactions database so, again trends in unit size cannot be determined. A trend in unit distribution, however is observable. In 1990 the breakdown of private non-landed properties was roughly 80% apartments and 20% condominiums, but since then roughly 80% of all new private non-landed units are condominiums, while only 20% are apartments. This reveals an overall shift toward larger condominium units in the private non-landed sector, and when considered alone, a shift toward higher residential land use footprint.

The largest residential segment in Singapore, public housing, has changed dra-

Table 3.2: Breakdown of existing and new units, 1990–2011

Housing Type	**Fraction of Existing Units** 1990	**Fraction of New Units** 1990	**Fraction of New Units** 2011
1 Room HDB	5%	0%	5%
2 Room HDB	7%	0%	4%
3 Room HDB	41%	0%	10%
4 Room HDB	32%	41%	68%
5 Room HDB	11%	36%	13%
5+ Room HDB	4%	23%	0%
Public	100%	100%	100%
Detached House	10%	10%	10%
Semi-Detached	30%	30%	30%
Terrace House	60%	60%	60%
Landed	100%	100%	100%
Apartment	80%	20%	20%
Condominium	20%	80%	80%
Non-Landed	100%	100%	100%

Figure 3-4: Typical 4 room HDB units: 1990, 105 m^2 (left), and 2010, 90 m^2 (right)

matically over the past twenty years. Public housing data is reported annually by the HDB, and includes much finer grain detail than the private housing resources. From the HDB annual reports, the average floor area of each unit type is gathered and recorded in Table 3.5. The trend is a roughly linear downsizing of unit floor area among the largest public units, 4 rooms and larger. Floor areas for these new units are roughly 15% smaller in 2011 than in 1990, see Figure 3-4 for a typical example.

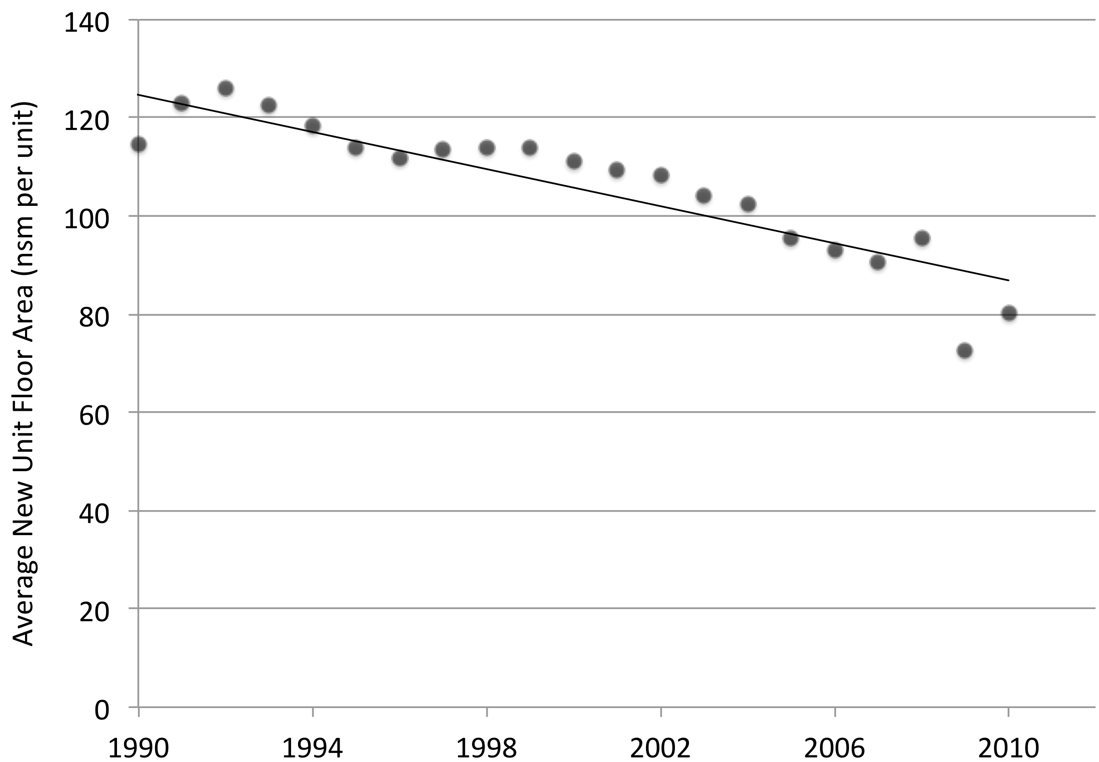

Figure 3-5: Average net floor area for a new HDB unit, 1990–2010

Also, the distribution of new HDB completions has shifted significantly toward smaller unit types over the last two decades, see Table 3.2. These two trends—smaller floor plans within the same unit type, and a shift toward smaller unit types—result in a significant reduction in average floor area per new unit over the last two decades. Figure 3-5 shows the decrease from 123 net square meters in 1990 to 85 net square meters in 2010.

The reason for this shift toward smaller public housing units is not the result of decreased space demands among Singapore residents. In fact, the opposite is true.

Wong and Yap conducted a survey of housing aspirations among Singapore residents and found significant desire for larger and more prestigious accommodations [66]. However, the realities of income, age, and housing cost have led many residents to stay in their current homes or even downsize to smaller units when their children leave home. It appears, then, that the reason for shrinking public housing units is one part of a nuanced policy strategy to manage housing aspirations. Public housing supply is focused on low to middle income groups that are trending toward smaller family sizes, so smaller units—both in number of rooms and floor area—are acceptable and affordable, while private housing provides an opportunity for wealthier households to satisfy their ambitions. But, because private housing supply is limited and costly, units tend to be moderate in size for cost reasons. The overall effect is a market-based means for incentivizing space efficient housing while still meeting growing aspirations of upwardly mobile residents.

3.3.2 Plot Ratio

Plot ratio, the ratio of building gross floor area to site area, is one of the most important factors affecting land use footprint, and because it is directly set by zoning policy it is one of the strongest levers the Singapore government has to influence land use efficiency. This section details how plot ratio has been used to decrease residential land use footprint throughout the nation's brief history.

A survey of Singapore's housing stock identified 12 typologies of housing, which were physically modeled to study and compare built forms, and quantitatively analyzed for their plot ratio, site coverage, and height in stories. Photographs of the physical models are shown in perspective in Figure 3-6, identified in plan in Figure 3-7, and compared quantitatively in Figure 3-8, using the SpaceMate chart [67].

Before 1960, Singapore's housing stock consisted of two primary building typologies: the kampong and the shophouse. Kampong houses are a traditional vernacular structure often raised above ground on pilings, of timber construction and a thatched attap or corrugated metal roof. Units are typically clustered together to form informal streets and public spaces, see Figures 3-6 and 3-7, first row, left. The shophouse

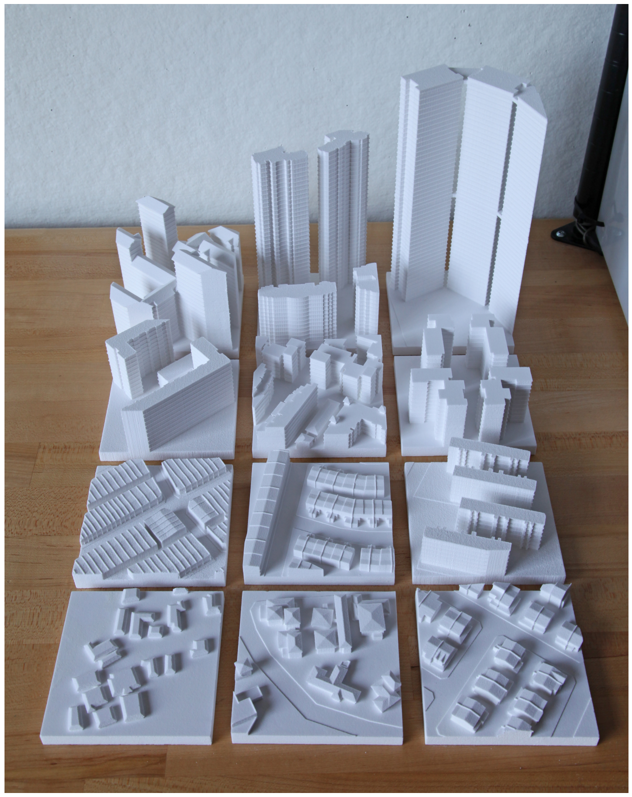

Figure 3-6: Typical Singapore housing typologies: form

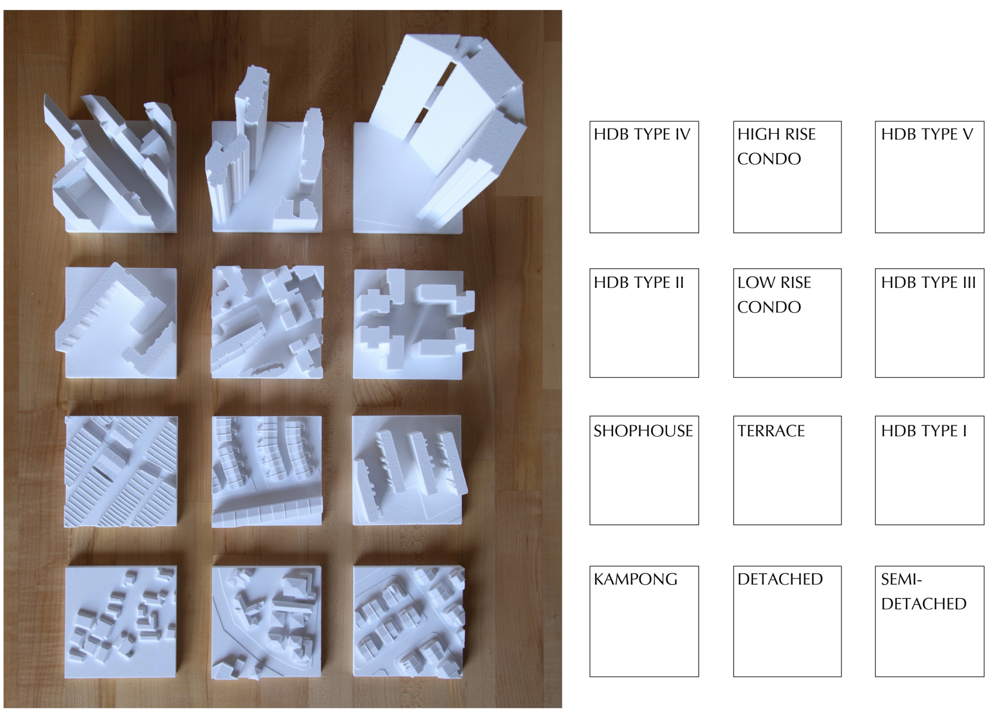

Figure 3-7: Typical Singapore housing typologies: plan

is another traditional southeast asian housing prototype, typically a two story masonry construction with shop space on the ground floor and living space on the upper floor. Units are arranged densely, in block-long rows with shared party walls, covering nearly all of the available site area, see Figures 3-6 and 3-7, second row, left. While a few neighborhoods of these housing typologies remain today, neither model was sufficient to house the ballooning population of post-independence Singapore. In fact, to alleviate the dangerously crowded conditions found in many such neighborhoods the URA carried out an urban renewal program to demolish and redevelop most of these areas, meaning the traditional housing typologies play a negligible role in residential land use today.

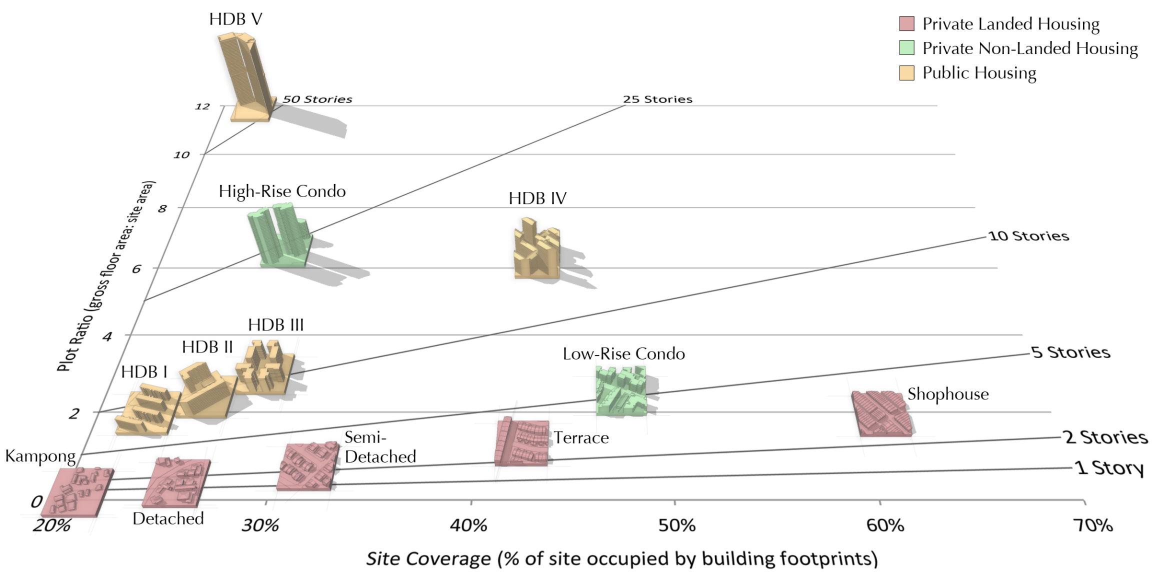

Figure 3-8: Typical Singapore housing typologies in SpaceMate chart, comparing site coverage, plot ratio, and height

Upon gaining independence, the Singapore government turned its attention to the rapidly increasing population and severely lacking housing supply. Rather than allow private development to propagate the existing kampong and shophouse models across the entire island, which would have limited plot ratios to less than 2.0, the government pooled its resources to form the Housing Development Board, an entity with sufficient funding and power to establish a comprehensive public housing program. Referencing Leung's [68] study of the HDB's design evolution, between 1960 and today there have been five distinct generations of HDB housing typologies, defined in Table 3.3.

Table 3.3: HDB generations, adapted from [68]

Gen.	Description	Time	Plot Ratio
I	Composition of simple generic blocks	1960–1966	2.0–2.8
II	Building blocks as a tool for urban design	1967–1981	2.4–2.8
III	Tightening of sizes of precincts	1982–1990	2.8–3.0
IV	Diversification of design	1991–present	2.8–6.0
V	Super-high density redevelopments	2000–present	3.5–12.0

While the extremes of HDB plot ratios vary greatly over the five generations, Leung states that the average plot ratio has remained very near 2.8 between 1960 and 1990. Additionally, a qualitative review of the Master Plan 2008 [69] shows most public housing sites zoned for a maximum plot ratio of 2.8. Since 1990, however, more HDB projects are being built at higher plot ratios, especially redevelopments near the city center. In the model, it is therefore assumed that the average plot ratio of the existing stock in 1990 is 2.8, but the input plot ratio increases linearly from 2.8 to 3.0 between 1990 and 2011, owing to an increasing fraction of new HDB buildings being of the higher density redevelopment type. See Tables 3.4 and 3.5 for the initial and input plot ratios, respectively.

In order to retain some variety in housing stock, as well as to appeal to the affluent and upwardly mobile population, Singapore has always maintained a small share of high-end private housing. Private housing comes in two distinct varieties: landed and non-landed. Landed housing is by far the most expensive and least dense housing class in Singapore. Even with its exorbitant pricing, a study of residential land utilization criticizes that the government is losing valuable housing potential and revenue through land sales for such low density development [70]. As a result, the total amount of landed private housing has been strictly limited, and is unlikely to grow significantly in the future.

Before 1990 private housing represented a mere sliver of the total housing stock, but since 1990 the provision of new non-landed private housing has been consistently increasing, even while the provision of new public housing units fell sharply after 1999, see Figure 3-3. The result is that for the past decade new private housing units have exceeded new public housing units in sheer numbers. This means that the private fraction of the total housing stock is growing, significantly. So today, more than ever, the density trends in private housing have a profound effect on total residential land use.

Data for private housing plot ratio was gathered from government land sales for residential development [71, 72, 73]. The data show no particular trend in density change for landed properties or apartments, so the average of all recorded plot ratios was taken for each property type and recorded in Table 3.5. Also, since no trend was identified, it is assumed that the average plot ratio of the housing stock in 1990 was equal to the current value, see Table 3.4. There is, however, a distinct trend in increasing density of private condo developments, shown in figure 3-9. New condominiums increase linearly in average plot ratio from roughly 2.2 in 1990 to about 3.5 in 2012. This change serves to decrease the residential land use footprint over the modeled period.

3.3.3 Grossing Factor

The final element necessary to model the historical land use footprint and mean redevelopment time is the grossing factor. Grossing factor is the ratio of gross floor area to net floor area. While net floor area can be thought of as rentable space, and is usually the figure referenced when renting or buying a home, gross floor area is the total built area. Gross floor area includes all rentable and non-rentable space. In addition to the net floor area, gross floor area includes community and recreational spaces, lobbies, hallways, stairs, elevators, the thickness of walls, and in some cases parking structures.

Ideally the grossing factor for each of the housing types considered would be calculated by analyzing typical floor plans and site plans of entire residential developments. This information, however, is not readily available for a large enough sample of buildings to make a conclusive estimate of the grossing factor. Instead, the grossing factor

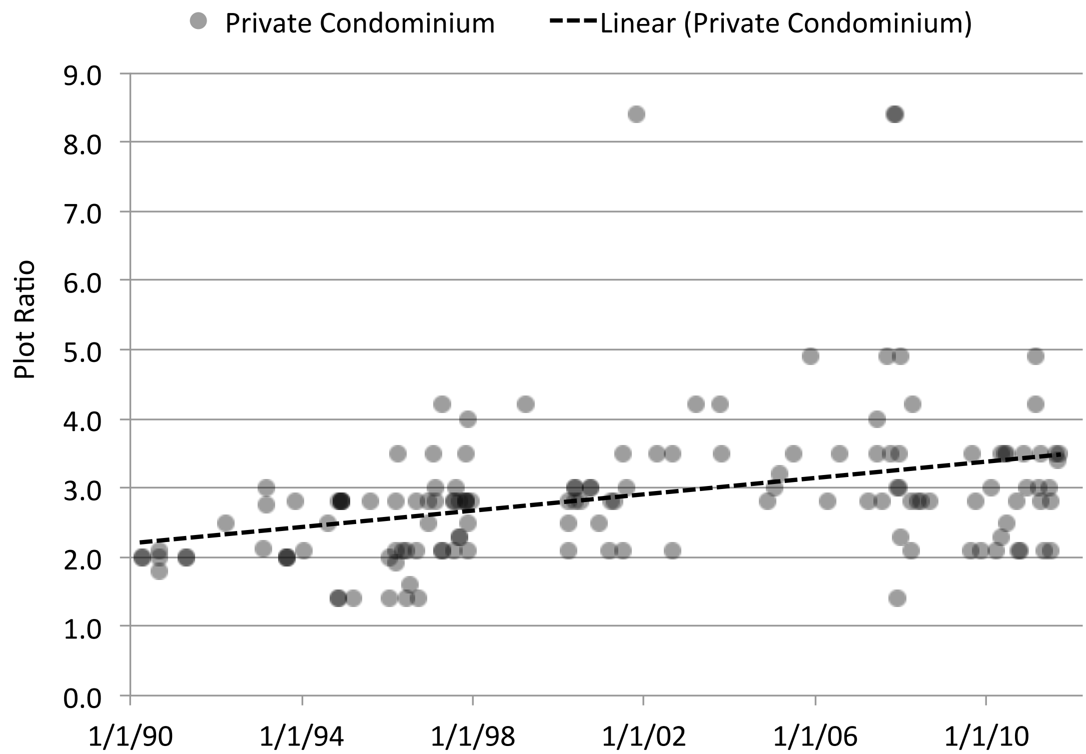

Figure 3-9: Private condominium plot ratio trend

in this modeling exercise is used a scaling factor to calibrate the model to known input and output data.

In addition to knowing the aforementioned model inputs—unit completion rate, lifetime, average floor area per unit, and average floor area—the ultimate output of the model—total land area for each of the housing types—is also known. This data was gathered spatially, georeferencing the 2008 Master Plan map in a Geospatial Information System (GIS), selecting the appropriate housing types, and calculating their total land area. Figure 3-10 shows the spatial distribution of three major housing types: public housing, private landed housing, and other housing. And Figure 3-11 shows the relative land areas of the the three measured housing types.

The master plan does not contain sufficient information to separate private non-landed housing from undeveloped residential land, so the model is calibrated using the two known quantities: total public residential land area, and total private landed residential land area. The grossing factor for these two housing types is adjusted

Figure 3-10: Location of major residential land uses [69]

Figure 3-11: Relative area of major residential land uses [69]

until the ultimate modeled land areas match the spatially measured areas. In this case the corresponding grossing factors were 1.6 for public housing and 1.3 for private landed housing. These values are very plausible. The higher value for public housing represents the greater circulation requirement in large high-rise buildings, the common spaces and public spaces often housed on HDB sites, and the structured parking that is a common fixture in most HDB estates.

Finally, since the data is not available, an assumption must be made for the grossing factor of private non-landed housing. Apartments and condominiums are typically in large high-rise buildings like public housing, so 1.6 is a fair starting point. However, private developments often have significant amenities that are not found in their public counterparts, including swimming pools, athletic facilities, and significantly more structured parking. For these reasons, the grossing factor for private non-landed housing is assumed to be 1.7.

3.4 Model Inputs

For reference, the model inputs are collected into the following two tables. Table 3.4 shows the initial conditions of the model, describing the existing housing stock in 1990. Table 3.5 details the input parameters over the period 1990–2011. The results of the model are presented in Chapter 4.

3.5 Assumptions and Limitations

This model makes several simplifying assumptions. The housing stock is disaggregated into only three sub-types, while in fact there are at least 12 typical housing types present in the stock, see Figure 3-7. This is largely a result of the level of aggregation in available data. Also, where time-series data does not exist, a general assumption is made that the trend is constant at the mean value of the available data. This assumption is made specifically with regard to the floor areas and plot ratios of private landed housing, where no data for the time of construction is available.

Table 3.4: Initial model parameter conditions, 1990

Housing Type	**Avg. Net Floor Area** $m^2/unit$	**Grossing Factor** $dmnl$	**Avg. Gross Floor Area** $m^2/unit$	**Average Land Area** $m^2/unit$	**Plot Ratio** $dmnl$
1 Room HDB	30	1.6	48	17	2.8
2 Room HDB	45	1.6	72	26	2.8
3 Room HDB	65	1.6	104	37	2.8
4 Room HDB	105	1.6	168	60	2.8
5 Room HDB	130	1.6	208	74	2.8
5+ Room HDB	145	1.6	232	83	2.8
Public	85	1.6	137	49	2.8
Detached House	467	1.3	607	867	0.7
Semi-Detached	309	1.3	402	335	1.2
Terrace House	228	1.3	296	197	1.5
Landed	292	1.3	380	346	1.1
Apartment	99	1.7	168	70	2.4
Condominium	124	1.7	211	96	2.2
Non-Landed	104	1.7	177	75	2.3

Finally, the total allotted residential land area defined in the 2008 Master Plan—12,890 hectares—is considered to be a constant upper limit. In reality, this allotment will likely change in future versions of the Master Plan given trends in residential, commercial, industrial and recreational land use demands as well as land-reclamation supply efforts.

One major limitation of the described model is caused by the lack of spatial land-use data over the time period in question. As a result, the model can only be calibrated in its final state. Subsection 3.3.3 details the process by which the grossing factor was used as a universal, constant scaling factor to calibrate the model. This means that actual changes in grossing factor cannot be taken into account by the model in its current formulation. Further spatial data, at various times throughout the simulation period would be required to correct for this phenomenon.

The final, and most significant limitation of this model is the use of exogenous unit completions as a primary input. In Chapter 6 a methodology is described for simulat-

Table 3.5: New unit model parameters, 1990–2011

Housing Type	**Avg. Net Floor Area** *$m^2/unit$*	**Grossing Factor** *dmnl*	**Avg. Gross Floor Area** *$m^2/unit$*	**Average Land Area** *$m^2/unit$*	**Plot Ratio** *dmnl*
1 Room HDB	30	1.6	48	17–16	2.8–3.0
2 Room HDB	45	1.6	72	26–24	2.8–3.0
3 Room HDB	65	1.6	104	37–35	2.8–3.0
4 Room HDB	105–90	1.6	168–144	60–48	2.8–3.0
5 Room HDB	130–110	1.6	208–176	74–59	2.8–3.0
5+ Room HDB	145–125	1.6	232–200	83–67	2.8–3.0
Public	123–85	1.6	197–136	70–45	2.8–3.0
Detached House	467	1.3	607	860	0.7
Semi-Detached	309	1.3	402	332	1.2
Terrace House	228	1.3	296	198	1.5
Landed	276	1.3	359	305	1.2
Apartment	99	1.7	168	70	2.4
Condominium	124	1.7	210	96–60	2.2–3.5
Non-Landed	119	1.7	202	90–62	2.2–3.2

ing total new unit completions based on population changes and market conditions. At this time, there is no reliable way to apportion total simulated unit completions into public, private landed, and private non-landed fractions. Because the changing ratio of new public to private housing is a key factor influencing future land use in Singapore, the ability to determine public and private unit fractions represents a critical next step in this research. That ratio is likely dependent on the growing affluence of the population, current market conditions, and housing policy. Future expansion of this research should seek to develop an endogenous means for generating private and public unit fractions.

Chapter 4

Planning & Residential Land Use: Results

The current distribution of residential land is presented graphically in Figure 4-1, and tabulated numerically in Tables 4.1 and 4.2.

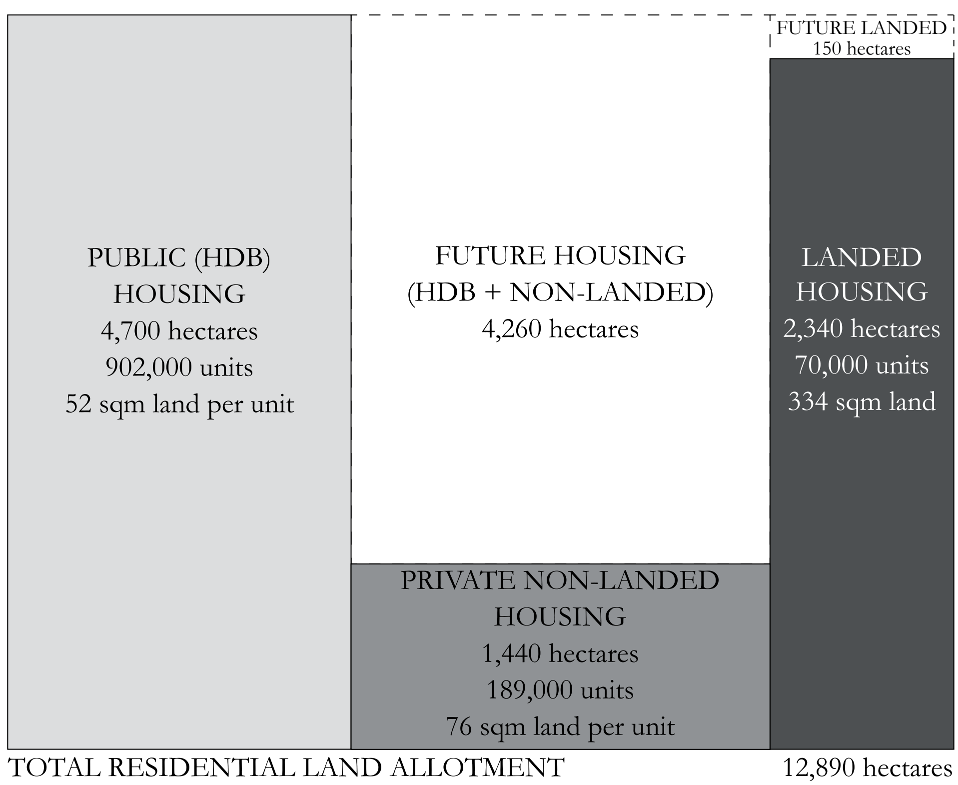

Figure 4-1: Relative area, unit count, and unit footprint of residential land uses

From Figure 4-1, it is apparent that Singapore has zoned ample future residential land to accommodate significant growth in its housing stock. Based on the per-unit land areas calculated in Table 4.1, the land allotted for future housing is sufficient for 565,000–825,000 additional residential units, and would support a population growth of 2.3–3.3 million people, based on an average unit occupancy of 4 people.

Table 4.1: Current residential land use footprint, Λ_r, 2011

Residential Type	**Land Area** *hectares*	**Housing Units** $x1,000$	**Land Area per Unit** $m^2/unit$	**Total Population** $x1,000$	**Land Use Footprint** $m^2/person$
Public (HDB)	4,700	902	52	3,126	15.0
Priv. Non-Landed	1,440	189	76	-	-
Priv. Landed	2,340	70	334	-	-
Future	*4,410*	*0*	-	*0*	-
Total Built	8,480	1,161	73	5,184	16.4

When compared to other major cities, a Singaporean's residential land use footprint is considerably smaller than a resident of Boston, London, and New York City, but roughly 50% larger than that of Manhattan—New York's central district—or Hong Kong, see Figure 4-2, where each value was calculated using Equation 3.1.

The comparison to other cities shows that Singapore's current housing stock is very land efficient, especially its private non-landed and public housing. And since only a small fraction of the future residential land allotment is designated for landed housing, it can be assumed that the future of housing in Singapore will continue the current trend of land use efficiency.

One trait, unique to Singapore, is a larger land use footprint within the central district than the city as a whole. The majority of Singapore's low density landed housing, which was built on the historical perimeter of the city, is now in the city's central area because over the last half century the entire island has become urbanized, see Figure 3-10. For several decades, new development has concentrated around the island's periphery, and has consisted of predominantly high density public and private housing, resulting in a relatively lower residential density near the city center.

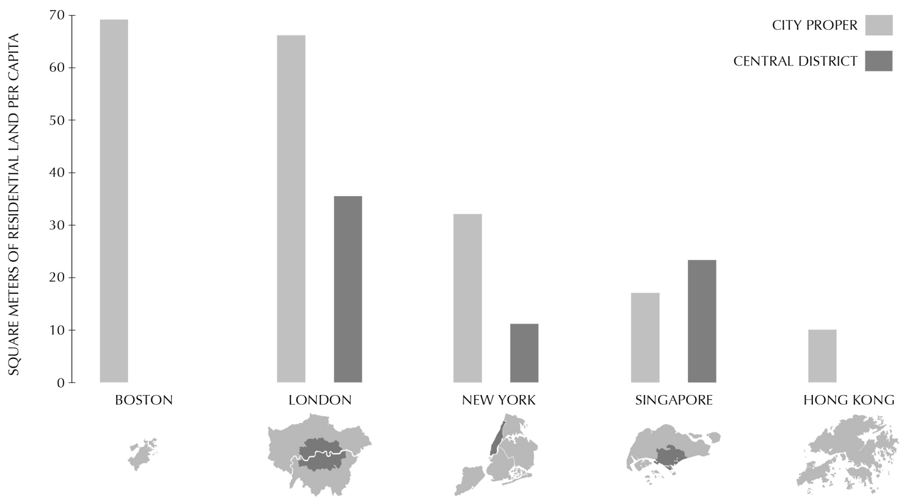

Figure 4-2: Land use footprint for Boston[1], London and its Central Boroughs[2,3], New York City and Manhattan[4,5], Singapore and its Central Region[6,7], and Hong Kong[8,9]

While these results suggest that Singapore has structured its urban planning in a way that has kept housing very land efficient and left ample room for future development, it is possible to quantify the potential for future change through the measure of mean redevelopment time. Calculated in Table 4.2, Singapore's current residential mean residential redevelopment time, T_r, is 11.2 years.

Table 4.2: Current mean residential redevelopment time, T_r, 2011

Residential Type	**Land Area, LA_x** *hectares*	**Land Area Fraction, ϕ_x** %	**Redevelopment Time, τ_x** *years*
Undeveloped, u	4,410	34%	5
Public, pub	4,700	36%	10
Private, $priv$	3,780	29%	20
Total	12,890	100%	$T_r = 11.2$

[1]Land Area and Population: http://140.241.251.212/PDF/ResearchPublications//Rpt592.pdf
[2]Land Area: http://data.london.gov.uk/datastore/package/land-use-ward
[3]Population: http://data.london.gov.uk/datastore/package/daytime-population-borough
[4]Land Area: http://www.nyc.gov/html/dcp/html/landusefacts/landusefactshome.shtml
[5]Population: http://www.nyc.gov/html/dcp/html/census/demo_tables_2010.shtml
[6]Land Area: http://www.ura.gov.sg/MP2008/
[7]Population: http://www.singstat.gov.sg/pubn/popn/c2010acr.pdf
[8]Land Area: http://www.pland.gov.hk/pland_en/p_study/comp_s/lup/index_e.htm#table_2
[9]Population: http://www.yearbook.gov.hk/2000/eng/hkfacts/index.htm

4.1 Mean Residential Redevelopment Time Trend

Because the redevelopment times for each residential land use type are unique to a single city, mean redevelopment time is not a useful measure to compare between cities. Rather, it is useful to observe how the mean redevelopment time of a city has changed over time. As a city grows and develops, it is expected that mean redevelopment time will increase. In fact, the only way for the value to decrease is to demolish less flexible land uses and replace them with either undeveloped or more flexible land uses. Figure 4-3 confirms that Singapore's mean redevelopment time has been increasing over the past two decades.

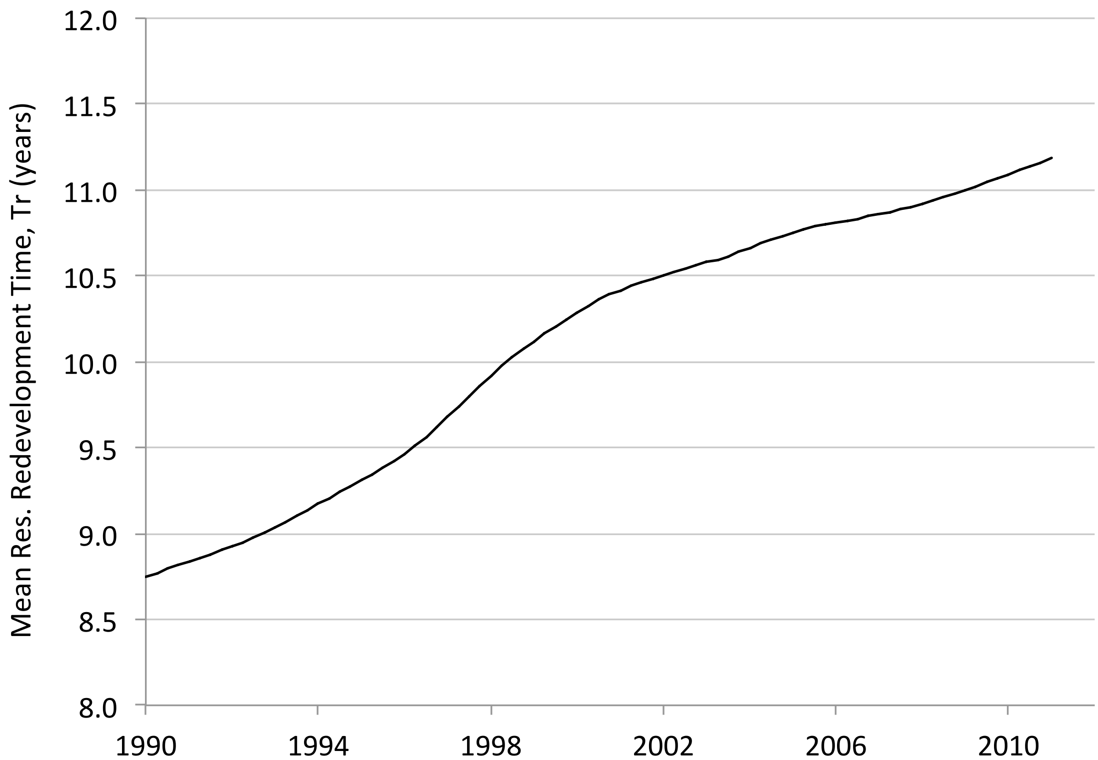

Figure 4-3: Mean residential redevelopment time, T_r, 1990–2011

A more relevant indicator of new development efficiency, however, is the rate of change of mean redevelopment time. Periods of rapid increase are the result of increased land development or a shift towards less flexible uses, particularly private housing. Figure 4-4 shows the annual rate of change in mean redevelopment time between 1990 and 2011, calculated as the first order time derivative of mean redevelopment time, $\frac{dT_r}{dt}$. A clear behavior in the change of mean redevelopment time is readily apparent.

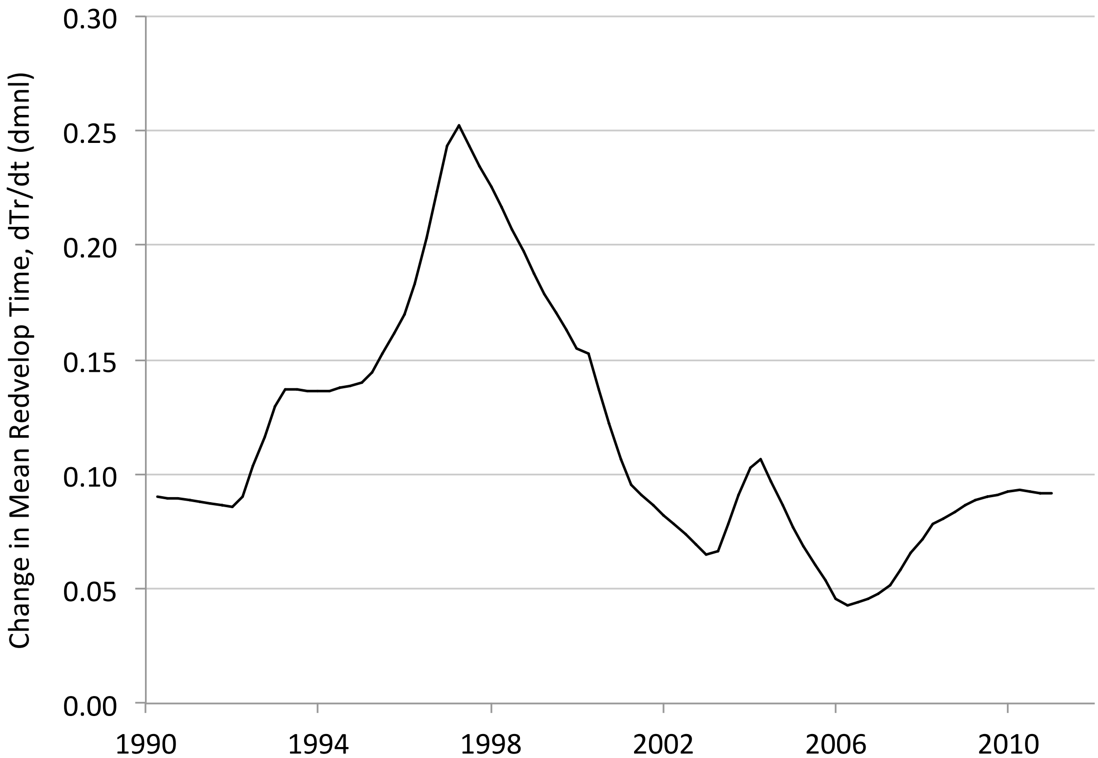

Figure 4-4: Annual change in mean redevelopment time, $\frac{dT_r}{dt}$, 1990–2011

From 1990–1997 the rate of change of mean redevelopment time increased significantly, reaching a maximum for the entire period. Then the trend reversed, and the rate of change fell dramatically reaching a minimum in 2006. Since then, the rate has been increasing gradually. Possible explanations for these changes will be presented in Chapter 5.

4.2 Land Use Footprint Trend

Figure 4-5 shows residential land use footprint from 1990–2011. The observed trend is an increase in footprint from 1990 reaching a maximum of 19.1 in 2003. The footprint levels off and then declines sharply beginning in 2004 and continuing to the present. The current footprint value of 16.4 represents a minimum for the entire modeled period. For land constrained cities like Singapore, understanding what leads to periods of increasing or decreasing residential land use footprint is very valuable to informing planning and housing policy in the future.

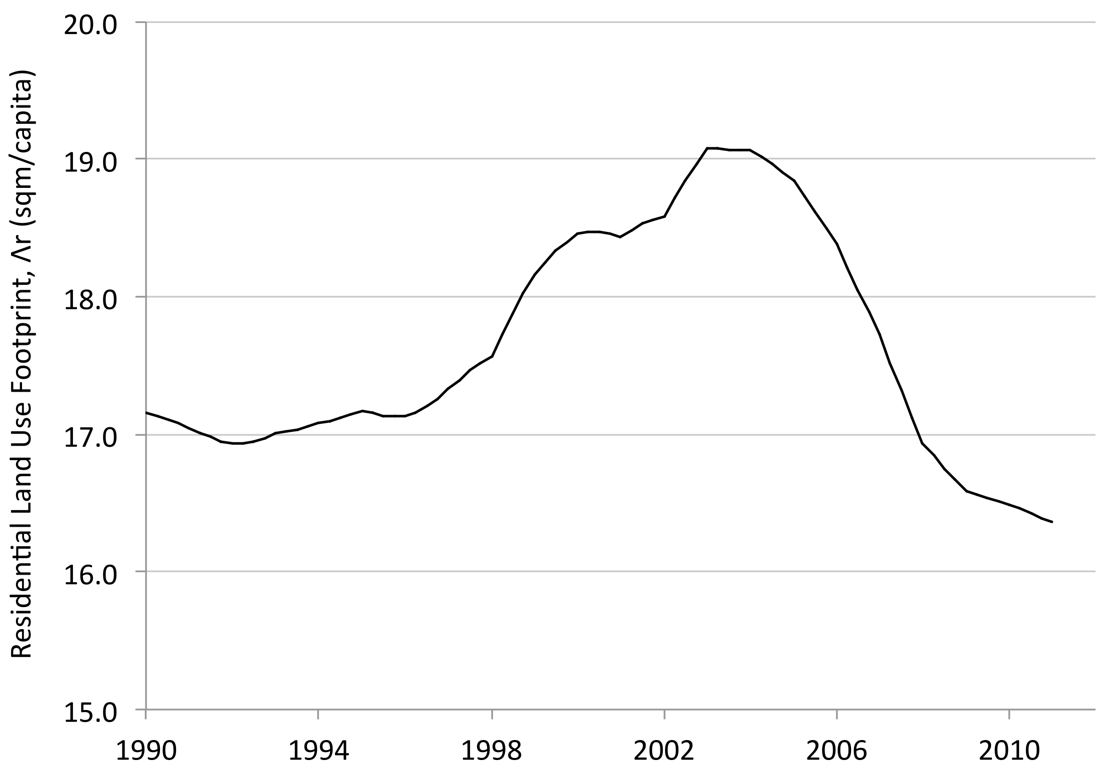

Figure 4-5: Residential land use footprint, Λ_r, 1990–2011

The trend observed between 1990 and 2011 reflects a period of growth, and then significant decline in residential land use footprint. As presented in Subsection 3.1.1, there are four primary factors that influence land use footprint: net floor area per unit, grossing factor, plot ratio, and occupant density. Chapter 5 addresses each of these factors, and their contribution to the recent trend in residential land use flexibility and footprint.

Chapter 5

Planning & Residential Land Use: Discussion

The results presented in Chapter 4 show encouraging recent trends in both mean redevelopment time and residential land use footprint. The rate of change in mean redevelopment time is currently about 0.09 years per year, among slowest rates of increase over the modeled period. This implies that the potential for redevelopment of residential land is decreasing much more slowly than it was during the late 1900s and early 2000s. Similarly, the overall residential land use footprint has fallen nearly 15% from its peak in 2003. Again, indicating that residential land is being used more efficiently today than at any time in the last 20 years.

As identified in Chapter 3, several planning changes have contributed to decreased residential land use footprint: smaller floor area per unit and smaller unit types in public housing, as well as higher plot ratios in public and private non-landed housing. But at the same time, other trends have served to increase residential land use footprint: a larger fraction of new units being private, and a shift towards larger condominium over apartment units. By examining the aggregate changes in average net floor area per unit, grossing factor, plot ratio, and occupant density for the entire housing stock, the overall effect of these competing trends is determined, and their contribution to the recent improvements in mean redevelopment time and land use footprint evaluated.

5.1 Contributing Factors

Despite new HDB flats shrinking—more compact floor plans, and more small unit types—the trend in average unit floor area for the entire housing stock is upward, see Figure 5-1. Between 1990 and 1998 the growth was significant, with the average housing unit swelling from 101.5 to 107.5 net square meters. This is the result of a shift toward more private non-landed housing, specifically condominiums, over the last two decades. Since 1998 the growth has leveled off to a nearly constant value of 108.5 net square meters per unit, resulting in a total increase of about 7%. Given the anticipated resurgence in new public housing units, this trend will likely bend downward toward smaller average unit floor area in the near future.

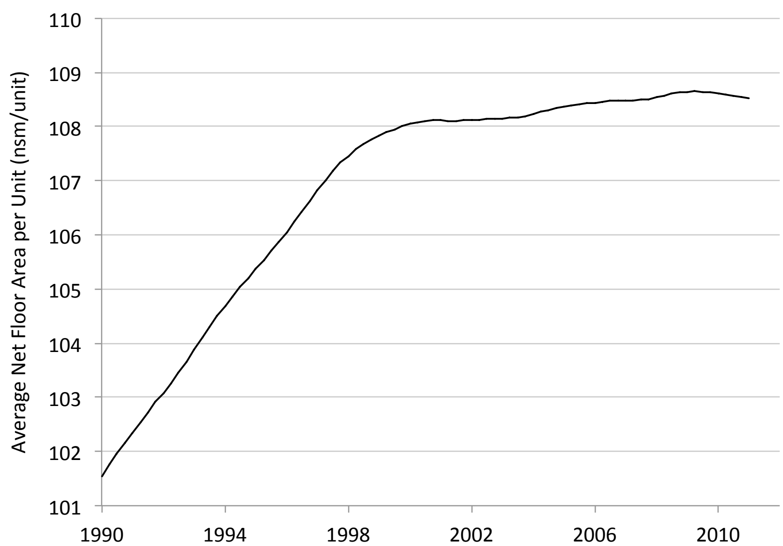

Figure 5-1: Average net floor area per residential unit, 1990–2011

Grossing factor is used as a constant scaling factor in this model, so there is very little change in the average value over the modeled period. While it is likely that grossing factors have varied in response to changing building codes and trends in parking provision, such factors were not considered in this study. The only change in grossing factor accounted for in this study is that caused by the changing distribution of residential units. The shift toward more private non-landed properties, those with the highest plot ratio, has caused the average plot ratio to increase slightly—about 1%—over the modeled period, see Figure 5-2.

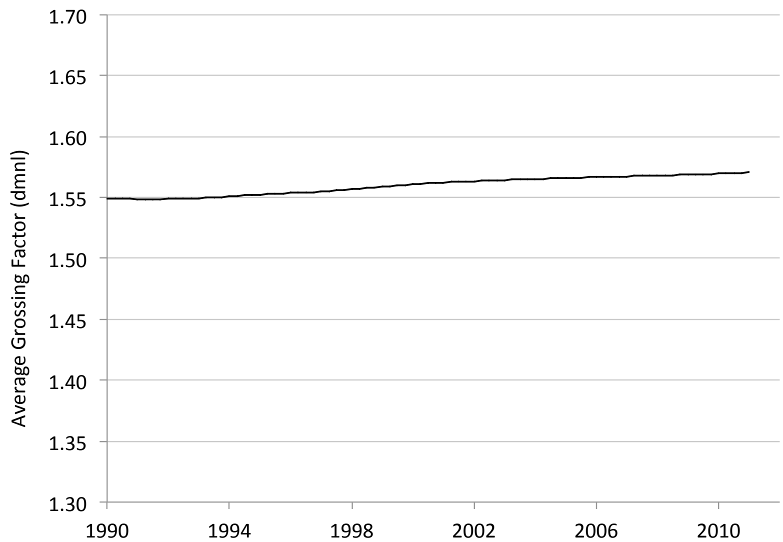

Figure 5-2: Average grossing factor, 1990–2011

Proactive planning has had a markedly positive effect on how densely residential land is developed in Singapore, with the average plot ratio of the entire housing stock increasing by almost 7% since 1990, see Figure 5-3. With relatively little new construction in the private landed housing sector, the ever-increasing plot ratio of new public and private non-landed developments has contributed significantly to the growth in the overall average.

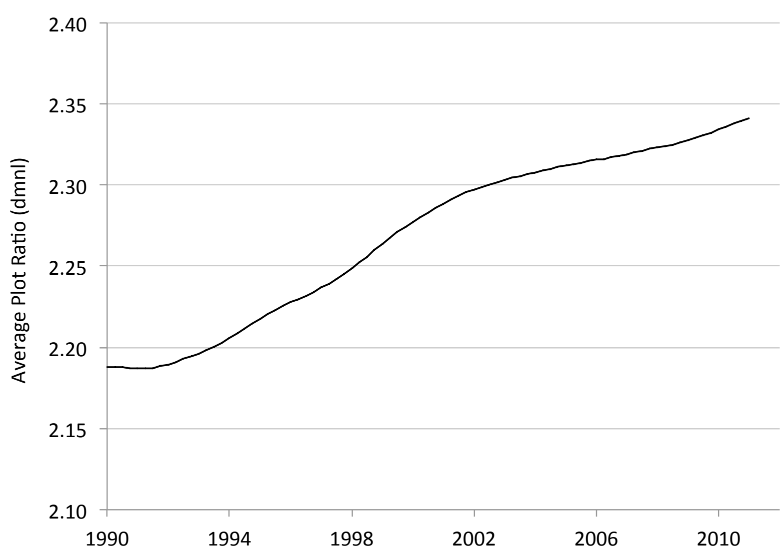

Figure 5-3: Average residential plot ratio, 1990–2011

When considered together, the trends in unit size (NFA), grossing factor (GF), and plot ratio (PR) combine to give the unit footprint (UF), the average land area occupied by a single residential unit—calculated as follows:

$$UF = \frac{NFA \times GF}{PR} \quad and \quad \Lambda_r = \frac{UF}{\rho_{occ}} \tag{5.1}$$

Figure 5-4 shows that the various trends in unit size, gross factor, and plot ratio essentially act to cancel each other out over the modeled period. The difference between the minimum (1990) and maximum (1998) recorded unit footprint represents a change of only 3%, not nearly enough to account for the 15% change observed in the residential land use footprint.

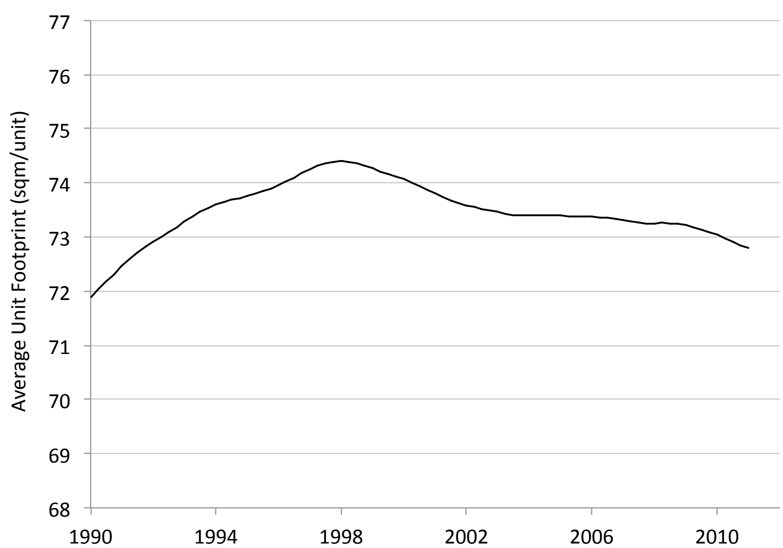

Figure 5-4: Average unit footprint, 1990–2011

As a result, the final factor affecting residential land use footprint, occupant density, must be considered. Occupant density is the average number of people per housing unit. It is important to note that it is not indicative of any particular housing unit, rather it is an aggregate measure calculated as the ratio of total population to total unit stock. Unlike net floor area per unit and plot ratio, which exhibit trends of varying growth, the average occupant density oscillates a full 1.25 cycles between 1990 and 2011. When overlaid with the residential land use footprint a nearly identical, albeit inverse, oscillation is observed, see Figure 5-5. While changes in unit size and plot ratio do have a direct effect on land use footprint, it is clear that over the last 20 years occupant density has been the factor most directly influencing land use footprint in Singapore.

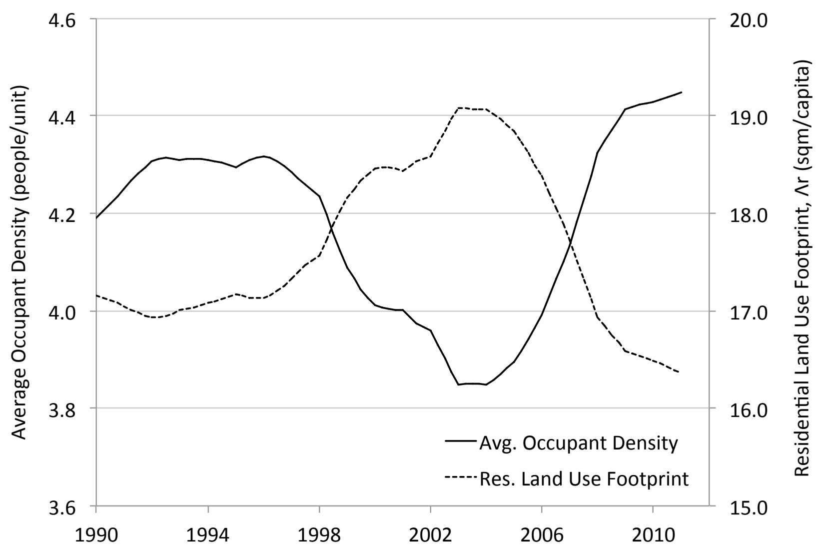

Figure 5-5: Average residential occupant density, 1990–2011

For the last eight years population growth, particularly of non-residents, has significantly outpaced the supply of new housing units, causing the observed increase in occupant density. The relative housing shortage indicated by this trend is the primary reason for the apparent decrease in residential land use footprint over the last decade. Unfortunately, this trend cannot last, as there is growing unrest among Singapore residents over the housing shortage, and the resulting increase in housing prices that it has caused, see Chapter 6.

5.2 Residential Land Use Planning: Conclusion

The results of this modeling exercise show that Singapore's approach to land planning has been successful in maintaining a small residential land use footprint, while meeting the housing needs of its population, and reserving ample land for future residential development. Centralized provision of the majority of housing from an early stage served to minimize land use through small units and high density developments.

While public housing units grew through the ‘80s and ‘90s, the recent trend has been toward smaller units and even higher plot ratios, addressing the demographics of an aging population and smaller families, as well as reflecting the growing cost of housing in the city.

The government’s limited release of land for private development has served to keep land cost very high, incentivizing private developers to build at the highest density allowable. Very strict limitations on the provision of land for low density residential development has also ensured that landed housing remains a very small fraction of the total housing stock, and its limited supply is reflected in its price.

By centrally monitoring and determining future housing provision, Singapore has a uniquely high level of control over the fate of its housing sector. Yet, despite a long-term trend of low residential land use footprint, the short-term view of land use and occupant density appears quite volatile, with both oscillating on the order of 15% over the last 20 years. As shown, these fluctuations are not the result of planning decisions, but rather the effect of market forces on a dynamic population. In order to understand the change in residential land use footprint over the last two decades, the effect of housing prices on household demand and government regulated unit supply must be examined. The structure for this comprehensive model is shown in Figure 5-6.

Up to this point, the Singapore housing market has been treated as a set of exogenous inputs, and their effect on the resource indicators has been generated. The remainder of this study is dedicated to modeling the primary housing market feedback loops that utilize social indicators of the housing market to inform supply (unit provision) and demand (price) policies, which in turn affect the housing market. The focus is on modeling housing policies to assess their contribution to price, supply, and demand fluctuations.

According to Tu & Wong, public housing policies have such a direct and immediate effect on the HDB resale price that non-policy factors—real income, GDP per capita, unemployment rate, the Asian Financial Crisis of 1998—have not played a significant role in price determination [17]. In turn, private market prices are heavily influenced

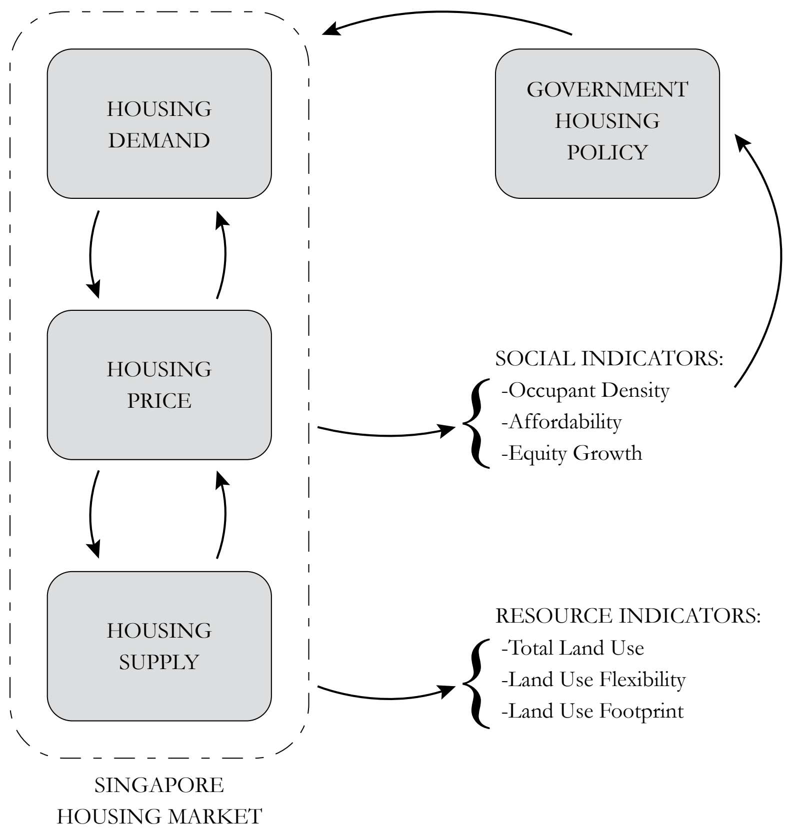

Figure 5-6: Singapore residential land use model

by the public resale trends [74, 75, 76, 77]. Table 5.1 identifies the main policy types available to the Singapore government to influence the housing market.

Table 5.1: Singapore housing policy options

Demand Policies	**Supply Policies**
Financing Terms	HDB Unit Supply
Grants and Subsidies	Private Land Sales (GLS)
Taxes and Duties	Subleasing Terms
Min. Occupancy Period	

Unlike many of Singapore's regulations, housing policy seems to be based on meeting two short-term goals: affordability and equity growth, which together drive public satisfaction with the general state of housing. While long-term land planning has determined the ultimate residential land availability, short term housing policies aimed at price moderation have destabilizing effects on mean redevelopment time and land use footprint. A better understanding of the relationships between policy and housing markets will allow for testing of policies to moderate fluctuations, and ensure a more stable future for Singapore.

Chapter 6

Policy & Residential Land Use: Methodology

While absolute land use footprint is of great importance to the sustainable development of a city, large cyclical fluctuations in the price and supply of housing can have widespread detrimental effects on overall resource demands and the local economy. Housing cycles are a nearly ubiquitous phenomenon in markets around the world, and are typically characterized by large swings in both residential price and the rate of new construction. During periods of price growth owners often participate in speculative purchasing, further increasing price, while the construction industry expands to meet the increase in demand. Alternately, when prices fall, ownership demand wanes and the construction industry contracts in response.

The primary consequence of continued price oscillation in residential markets is the resulting instability of the construction industry. Especially in areas undergoing significant growth, the expansion and contraction of the residential construction industry as a result of market oscillations can be quite significant. In response, many cities in developing regions, including Singapore, acquire much of their construction labor on short-term contracts from foreign or immigrant populations. In this way, the labor force can be adjusted in either direction relatively quickly by simply importing or exporting workers. As a city and its neighboring areas develop, however, rising labor standards make this practice more difficult and expensive. For this reason, it is in the best interest of cities to dampen their housing market cycles so as to stabilize the growth and maintenance of their construction labor force.

The secondary, and perhaps more interesting, consequence of housing cycles is their effect on the efficient use of natural resources. Glaeser, et al. note that "the inefficiency of a housing bubble comes from the misallocation of real resources—that is, the overbuilding of an area" [78]. In this case, 'real resources' refer to both developable land and construction materials. In an open market, where price growth is considered to be a proxy for increasing demand, suppliers continue to ramp up the rate of supply initiation as long as the price continues to grow. Unfortunately, due to the delay between initiating and completing new units of housing, considerable supply is completed after the peak price, when demand has already begun to fall. This additional supply further depresses the price, which further reduces demand. The result in many housing 'busts' is a relative over-supply of housing as units initiated during the 'boom' are completed.

In areas with unconstrained land resources, this over-supply takes the shape of partially finished housing developments: unoccupied houses, empty graded lots, unused roads and sewers. In land constrained cities, like Singapore, over-supply takes a distinctly different form. As housing supply increases and prices fall, people spread out to fill the available stock. Grown children move into their own homes rather than staying with parents; the elderly remain in their homes rather than moving in with children or to senior facilities. The mechanisms are not as important as the overall result; the average number of people per housing unit falls as the relative housing supply increases. This may not seem like a negative consequence, and in many developing cities where multiple families crowd into inadequate housing units, indeed it is a benefit. But in more developed cities like Singapore where land is severely limited, and the mean household size is already quite low, the over-supply results in a sub-optimal use of housing. The population utilizes more residential resources—land and construction materials—than it truly needs, or would demand given a constant price. Figure 6-1 confirms this effect occurred during Singapore's 1996 housing bubble.

The solid line in the graph shows the annual change in net floor area per capita,

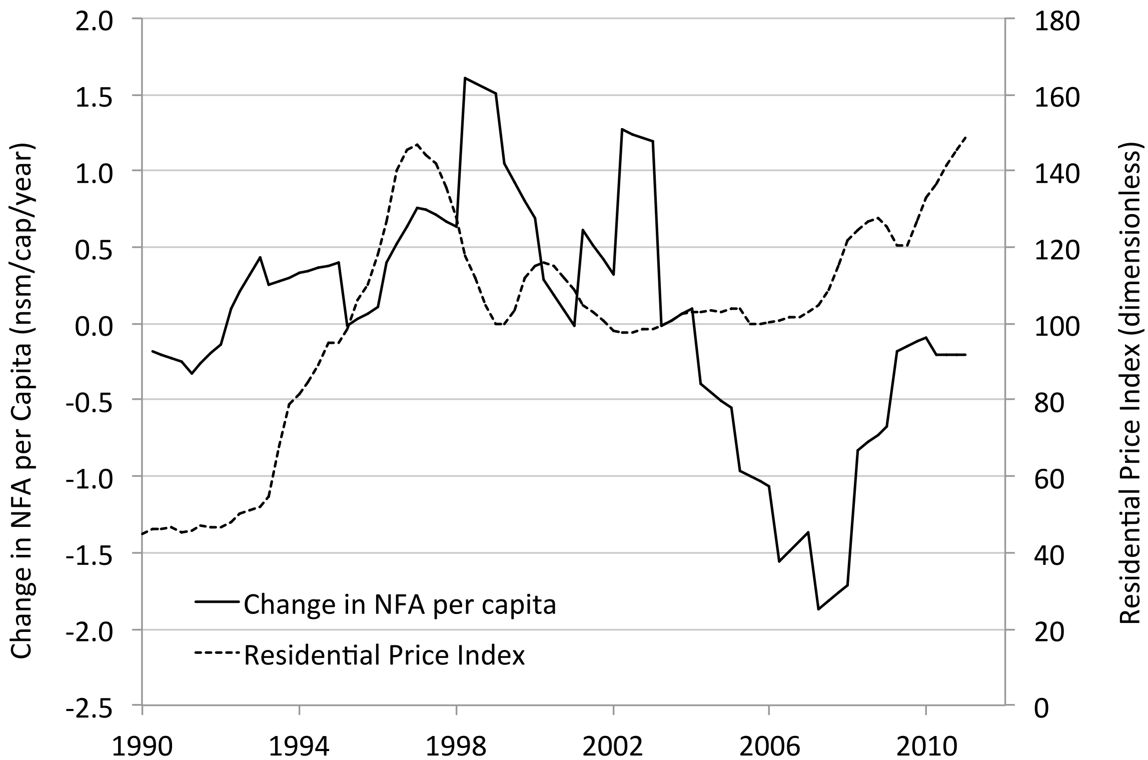

Figure 6-1: Change in net floor area per capita, $\frac{dNFAp}{dt}$, overlaid with Residential Price Index (RPI), 1990–2011

$\frac{dNFAp}{dt}$. This value is positive when new units being added to the stock are larger than average, and is negative when new units are smaller than average. For the same type of construction, larger unit areas represent proportionally greater material usage. This means that $\frac{dNFAp}{dt}$ can serve as a proxy for the relative material intensity—material use per capita—of new construction. The greater the $\frac{dNFAp}{dt}$, the greater the material intensity of units being completed at that time. Also, it is assumed that new unit construction takes 2–3 years from initiation to completion, so we expect that $\frac{dNFAp}{dt}$, which represents new floor area *completion* is shifted 2–3 years to the right of where new unit *initiations* would be. Imagining a 2–3 year shift of $\frac{dNFAp}{dt}$ to the left, it becomes clear that the peaks in material intensity correspond with the major price peaks, and the lowest material intensities correspond to periods of little growth in price.

In order to better understand the nature of housing cycles—both price oscilla-

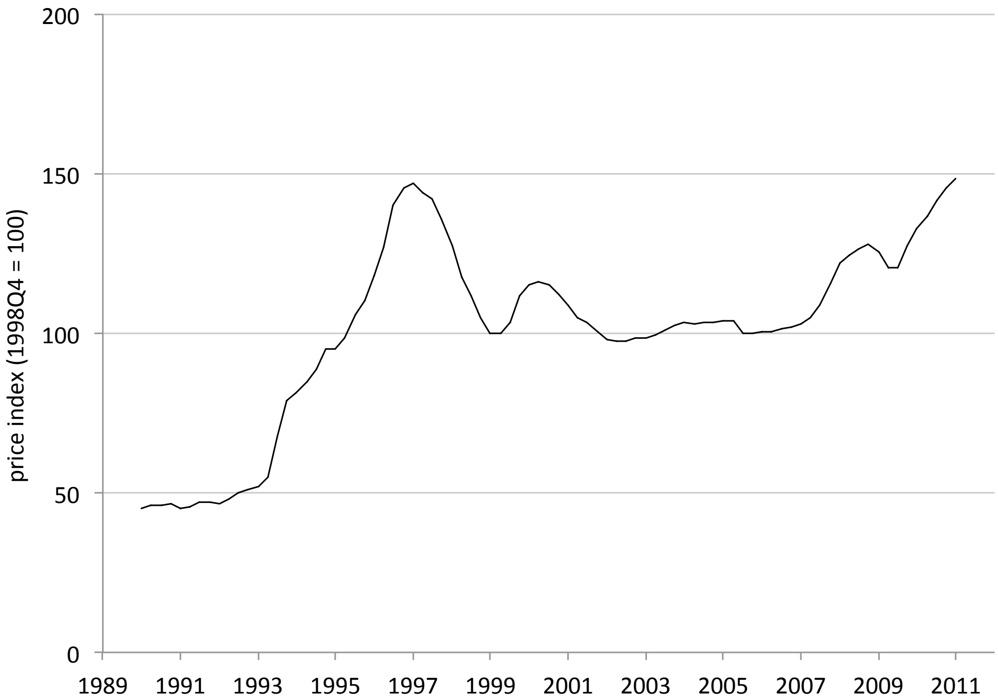

Figure 6-2: Singapore Residential Price Index (RPI): weighted average of Resale Public Price Index (RPPI, 80%) and Private Property Price Index (PPI, 20%) deflated by the Consumer Price Index (CPI) and normalized to 1998Q4 = 100 [18, 14]

tion, and the supply response—System Dynamics modeling is used to simulate the Singapore housing market from 1990–2011, see Figure 6-2 for the reference Singapore Residential Price Index over that period. For modeling, Singapore is an ideal choice because it represents one of the world's best examples of an urban laboratory. As an island nation comprised entirely of a single city, the data describing Singapore's physical and economic development is nearly unprecedented due to the parity of city-wide and national-wide reporting. Further, Singapore's pro-active governmental structure and it's unique, predominantly public housing landscape further simplify the complex interactions of construction, real-estate and economy. Yet, despite the relatively controlled nature of the system, Singapore's housing market has still experienced price oscillation and significant boom-and-bust cycles over the last 20 years, similar to those seen in freer markets. This suggests that the oscillatory nature of housing markets is endogenous to the structure of the system.

In this study, housing is treated as an undifferentiated commodity and the system structure is adapted from seminal System Dynamics literature on commodity dynamics [79] and stock management [64]. The basic premise behind both of these models is that physical and information delays create the non-intuitive, complex behavior of the systems they represent. Understanding and accounting for this delay structure is the key to moderating housing market cycles.

The goal of this model is to simply explain the variation of price and housing supply in Singapore, in order to identify policies and structures that might be applicable to residential markets, generally. The focus is on using known structures to reproduce observed behavioral trends—exponential growth, overshoot, and oscillation—rather than to minimize error. As identified by Tu and Wong, housing policies have had a significant influence on residential markets in Singapore, and the model shown here approximates two historical policy measures as exogenous drivers of the observed behavior [17].

6.1 Modeling Assumptions

There are two major assumptions inherent in the following model description: all housing, regardless of type, is considered as a single, undifferentiated commodity; and the Singapore population is considered only as an aggregate total— no differentiation of citizens, permanent residents, or non-residents is made. These assumptions were required because of limited data disaggregation, the desired simplicity of the model, and the need to prevent unique aspects of the Singapore housing markets from defining the model's behavior.

While the model can adequately address the aggregate supply, demand, and price of housing, the relative effects of a change in any one sector of housing or the population can not be determined. Special adaptations to the model structure are necessary to deal with changes in a single housing sector or population sub-group. Section 6.6 details an example of how modifying the availability of public housing for non-residents requires customized changes to the model's structure. Since relatively few policies will be tested, and the emphasis of this research is on understanding the overarching forces at play in general housing markets, rather than the interrelationships between Singapore's housing and population subgroups, the simple aggregate model is the preferred starting approach.

6.2 Commodity Dynamics

As a starting point for building a simple housing market model, the assumption was made that at a completely aggregated level—without differentiation for private/public, landed/non-landed, or small/large units—housing in a single, isolated city like Singapore could be treated as a commodity. Classical commodity models are rooted in the law of supply and demand, or as Adam Smith called it, the 'invisible hand of the market,' which guides individual actors to behave in a way that balances price, supply, and demand to an optimal equilibrium [37].

Figure 6-3 shows Smith's invisible hand in causal loop form. This method of diagramming was developed by Forrester as a visual form of displaying relationships, hypotheses, and assumptions inherent in System Dynamics models [55]. Each label represents a variable or parameter in the model, while each arrow represents the influence of one variable on another. *Ceteris paribus*, a '+' sign represents a positive relationship between variables, while a '-' sign represents a negative relationship. For example, the diagram in Figure 6-3 can be read as follows: "Holding all else constant, an increase in Price causes an increase in Profits," or conversely "Holding all else constant, an increase in Price causes a decrease in Relative Value."

In this case, the 'invisible hand' is a pair of negative, or balancing, feedback loops that tend to moderate price through the mechanisms of supply and demand. As price increases the relative value of a commodity decreases, decreasing demand, and subsequently decreasing price. Similarly, as price increases profits increase, producers increase supply, and subsequently decrease price. This general structure forms the basis of the Meadows' Dynamic Commodity Cycle Model, one of the earliest attempts to apply System Dynamics modeling to commodity markets in an attempt to explain persistent oscillation in price and production. Figure 6-4 is Meadows' adaptation of

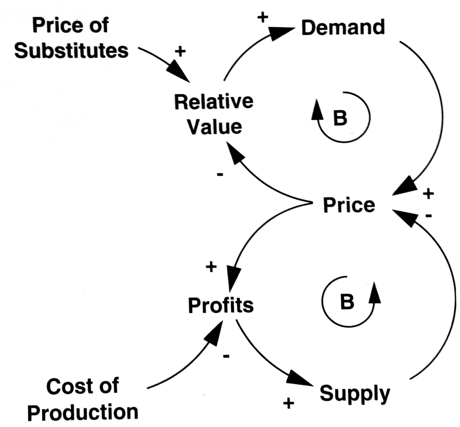

Figure 6-3: Adam Smith's invisible hand: feedback structure of markets [64]

the causal loop diagram shown in Figure 6-3, rotated 90 degrees clockwise.

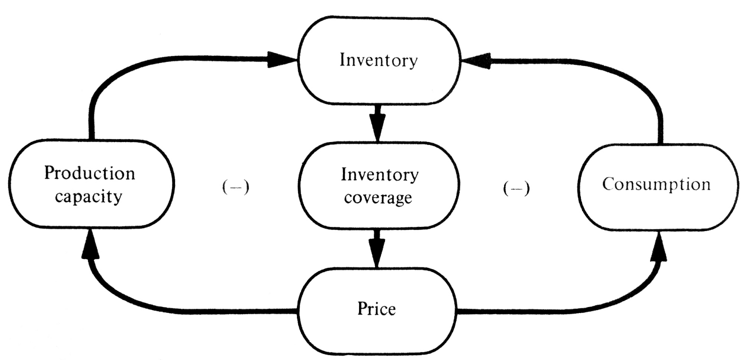

Figure 6-4: Feedback loop structure of production cycles [79]

In System Dynamics modeling, after determining the causal structure of the system, the next step is to build a stock-and-flow diagram. The stock-and-flow diagram serves as the graphic representation of the complete model. Figure 6-5 shows a simplified version of the stock-and-flow structure for the Dynamic Commodity Cycle Model.

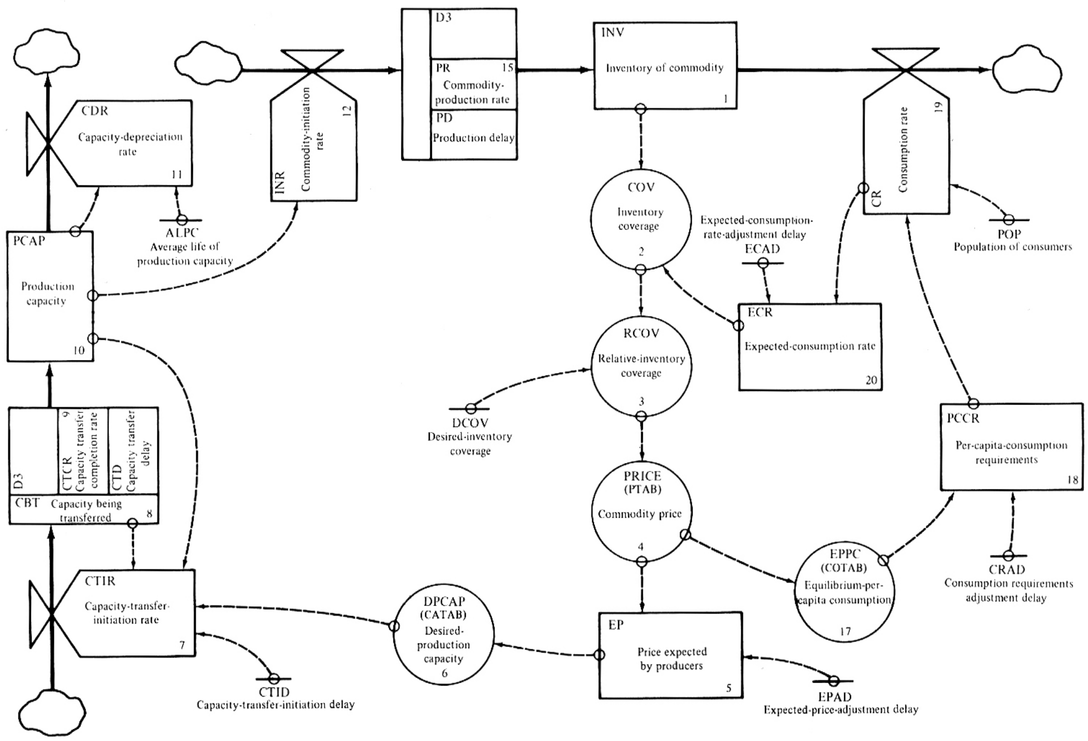

Figure 6-5: Simplified stock-and-flow diagram of the Dynamic Commodity Cycle Model, adapted from [79]

The model contains five distinct components, highlighted in Figure 6-6: (A) a supply chain for inventory, (B) a supply chain for production capacity, (C) a method for determining price, and (D & E) two balancing feedback loops. Loop D adjusts supply in response to changing price, while the Loop E adjusts per-capita-consumption rates in response to price. This basic structure is the foundation for the Singapore Housing Market Model, presented in Section 6.4.

Before adapting the commodity model to housing, one specific difference between the two sectors must be addressed. In the commodity model, Inventory Coverage and Consumption Rate are the driving parameters of price formation. In housing, however, the concern is not with the inventory of unoccupied housing units or the consumption rate of those unoccupied units. Instead, the variables of interest are the total number of housing units in service, and the total number of housing units

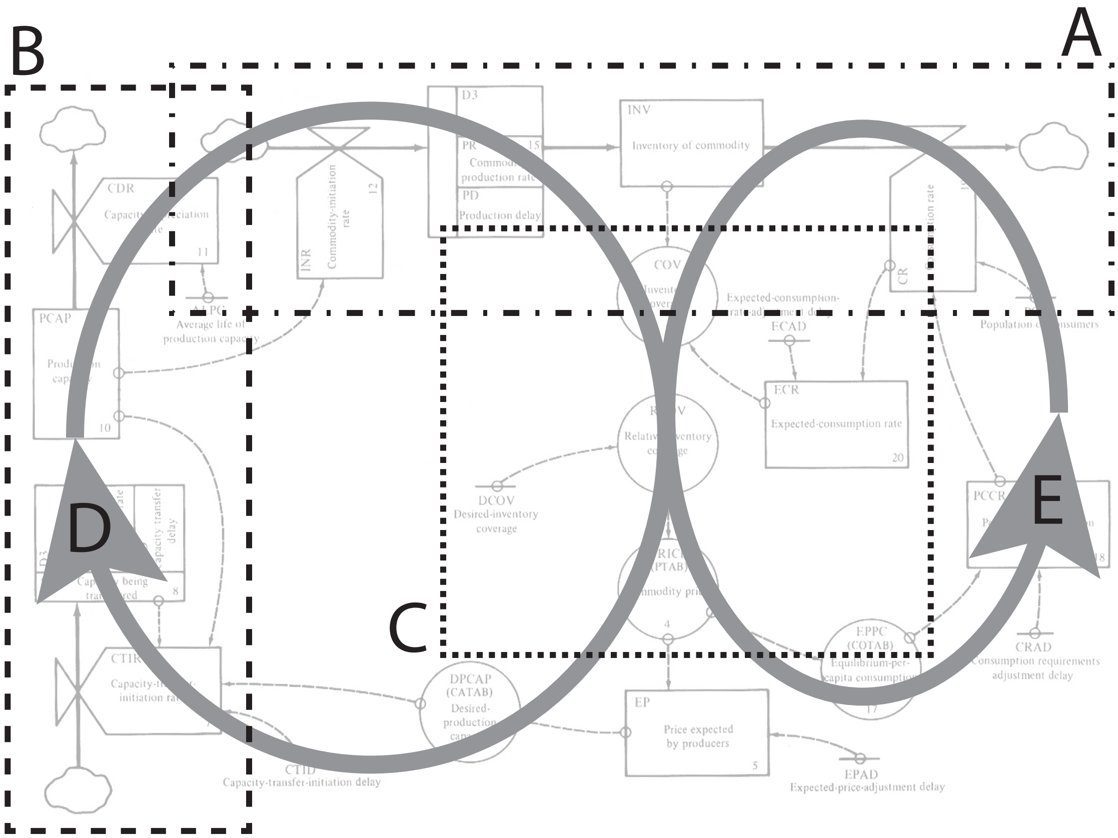

Figure 6-6: Five major components of the Dynamic Commodity Cycle Model

demanded by the population at any given time. This ratio of units demanded to units in service results in a normalized demand that can be used for price formation. Sterman's Stock Management Structure defines a generalized model structure for this type of system [64].

6.3 Stock Management

In addition to presenting a general structure for the maintenance of a stock, the Stock Management Structure adds several sub-structures for managing the supply line, shown in Figure 6-7. The two primary balancing loops, Stock Control and Supply Line Control, represent the structure of an ideally managed system. In this ideal system the Supply Line and the delay in Acquisition are fully accounted for. This means that the managers of the stock are taking the current work in progress into account when initiating new orders. In many housing markets, such as the United States, independent private developers have historically shown little or no consideration of the Supply Line in their initiation of new units [64]. In Singapore, however, housing supply is centrally regulated. Public units are initiated directly by the government through the Housing Development Board (HDB), and private unit provision is planned and permitted directly by the Urban Redevelopment Authority (URA). For this reason, the model of Singapore will include the idealized supply line management structures.

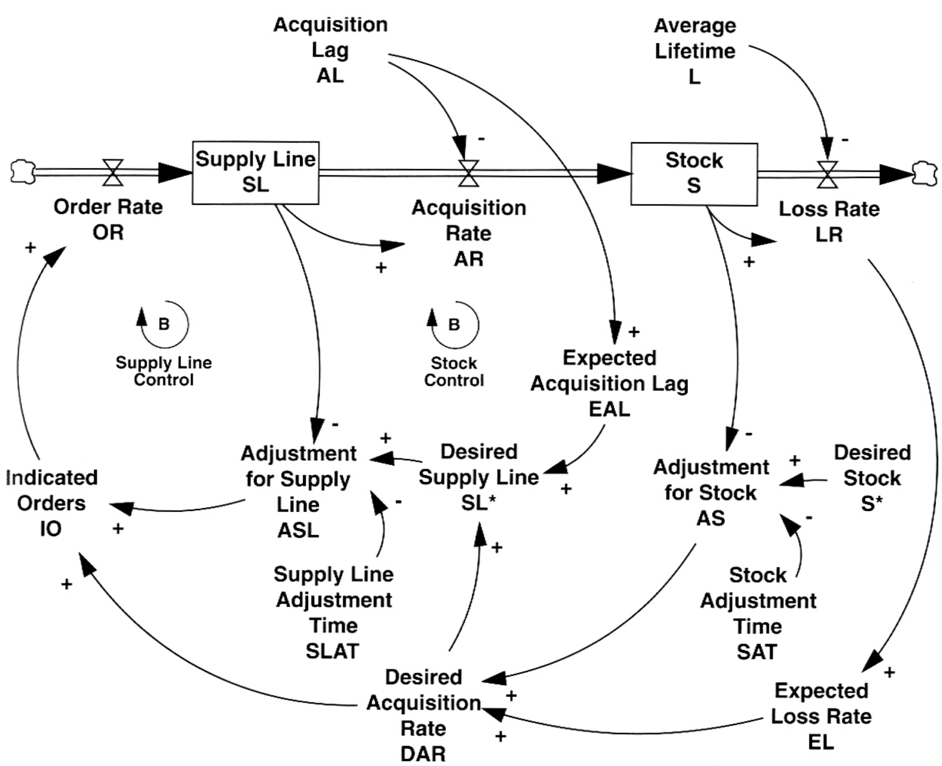

Figure 6-7: Stock Management structure [64]

Within these two structures, the Dynamic Commodity Cycle Model and the Stock Management Structure, all of the components required to formulate the Singapore Housing Market Model are present. The next section describes the adaptation of these general causal frameworks and stock-and-flow structures to the Singapore housing market.

6.4 Singapore Housing Market Model

The Singapore Housing Market Model is based in the same supply and demand causal loop structure as the general commodity model. Figure 6-8 shows the paired balancing feedback loops of supply and demand specified to housing. The notable differences are the replacement of Consumption with Desired Occupant Density, and the formulation of Price from Normalized Demand rather than Inventory Coverage.

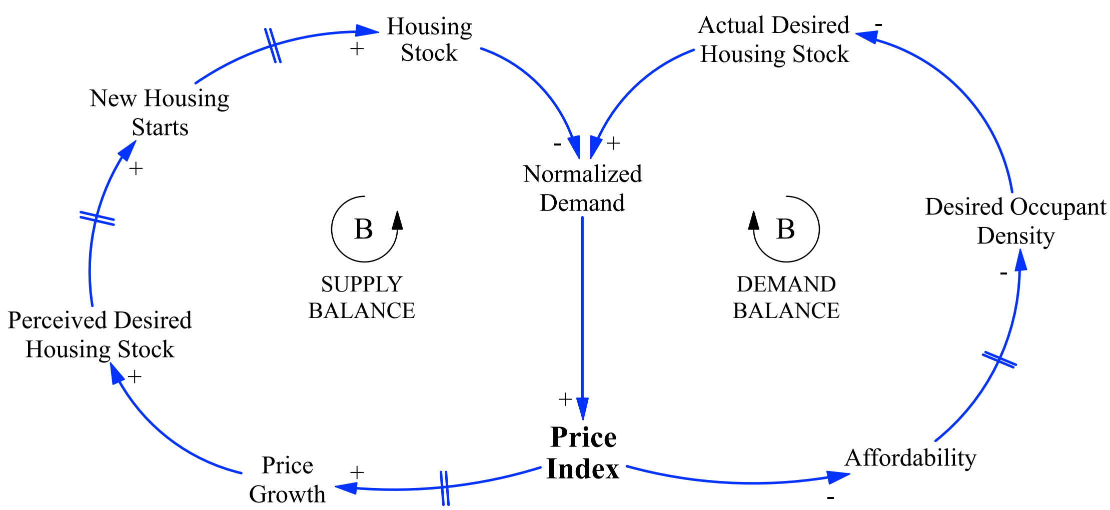

Figure 6-8: Housing supply and demand causal loop diagram

The fully expanded causal loop diagram for the Singapore Housing Market Model is shown in Figure 6-9 and described below. Here, the diagram has been expanded to include all of the relevant variables needed to explain the structure of the model.

In addition to the endogenously operating negative feedback loops, the full model includes three exogenous parameters, which disturb the system from equilibrium: Population, Reference Occupant Density, and Buyer Budget. Population is the total number of people residing in Singapore, including citizens, permanent-residents, and non-residents. Data for population is fed into the model, annually [14]. Reference Occupant Density is the average number of people per household that the housing planners (HDB and URA) deem to be appropriate, or normal. Finally, Buyer Budget is a normalized index that can be compared with the residential price index to

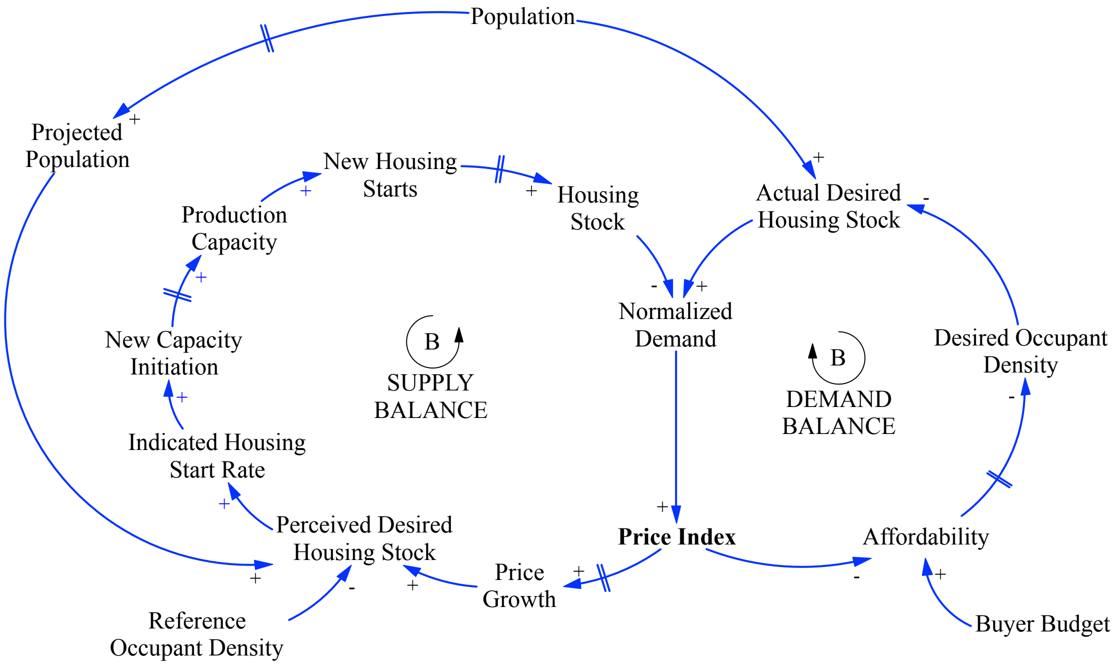

Figure 6-9: Current residential land use distribution

calculate affordability. Changes in Buyer Budget as a result of policy are discussed in Section 6.6.

Beginning with the Demand Balance Loop, analogous to Figure 6-6-E, for a constant Buyer Budget an increase in Price Index decreases Affordability. Occupants' only recourse to decreasing Affordability is to live more densely. As mentioned previously, this could take the form of multi-generational or multi-family living. As Affordability falls, the Desired Occupant Density (people per unit) increases, but with some delay. Occupants don't choose to change their living situation lightly, and decreased Affordability must persist for some time to change occupants' desires about how densely they should live. For a given Population, increasing Desired Occupant Density decreases the Actual Desired Housing Stock. When compared to the current Housing Stock, a decrease in Actual Desired Housing Stock results in a decrease in Normalized Demand, and lower Normalized Demand means a decrease in Price Index, analogous to Figure 6-6-C. As shown, by tracing the Demand Balance Loop, an increase in Price Index is ultimately balanced, or decreased by the negative feedback loop.

Similarly, an increase in Price Index is balanced, or decreased by the negative feedback of the Supply Balance Loop, analogous to Figure 6-6-D. Sustained increase in Price Index increases Price Growth, measured in percent per year. The Perceived Desired Housing Stock, as calculated by the suppliers, is a function of Price Growth, Reference Occupant Density, and the Projected Population. The trend of the Population is determined, and projected into the future. The Projected Population is then divided by the Reference Occupant Density to give a projection of the required future housing stock. This stock projection is then shifted up or down according to the current rate of Price Growth to give the Perceived Desired Housing Stock. Price Growth serves as a proxy for consumer demand, so positive Price Growth suggests additional demand, while negative price growth suggests lower demand. So as Price Growth increases Perceived Desired Housing Stock increases, in turn increasing the Indicated Housing Start Rate.

In an ideal scenario, the Indicated Housing Start Rate would be equal to the New Housing Starts, but in reality the construction industry must first adjust in order to meet the changing demands. An increase in Indicated Housing Start Rate increases the New Capacity Initiation rate, which after a delay results in increased Production Capacity, analogous to Figure 6-6-B. Increased Production Capacity allows for increased New Housing Starts, which, again after a delay for construction increases the Housing Stock, analogous to Figure 6-6-A. Holding Actual Desired Housing Stock constant, the increased Housing Stock decreases Normalized Demand, which decreases the Price Index, closing the balancing loop.

The full stock-and-flow structure of the Singapore Housing Market Model is shown in Appendix C, and the complete equation listing relating all variables is documented in Appendix D.

6.5 Input and Reference Data

In order to calibrate the model to the reference data, certain variables are input exogenously, and the non-linear elasticities between key variables are fine-tuned.

The total Singapore population is fed into the model as an exogenous input. Making population growth endogenous is well outside of the scope of this modeling exercise, although the model would benefit from certain aspects of the population being controlled by internal feedbacks. For instance, when construction capacity grows, population should increase as a result of new laborers immigrating from other countries. Again, the overall model could be improved by incorporating such factors into future versions.

In addition to the one endogenous data stream, data from the HDB and URA are used to initialize all the stocks to their 1990 values [18, 14]. Three variables are chosen as the reference indicators to which the model is calibrated: residential price index, unit initiation rate, and unit stock data, see Chapter 7. The model contains four non-linear elasticity functions, known in System Dynamics modeling as table functions. A best first estimate was made for each of these functions, and then they were each modified in order to calibrate the model to the reference time-series data, see Figures 6-10 and 6-11 for the final, calibrated table functions.

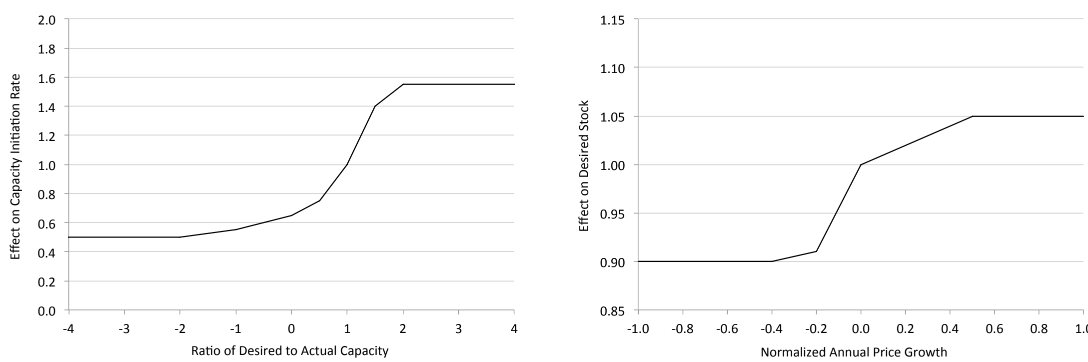

Figure 6-10: Effect of Ratio of Desired to Actual Capacity on Capacity Initiation Rate *(left)* and Effect of Normalized Annual Price Growth on Desired Stock *(right)*

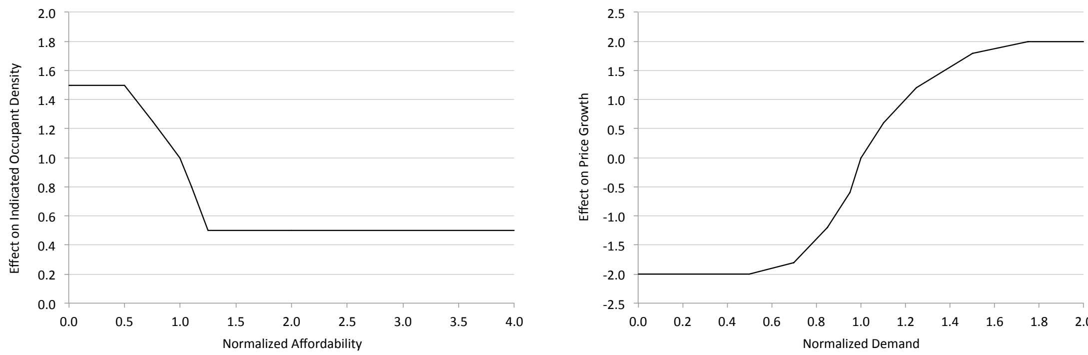

Figure 6-11: Effect of Normalized Affordability on Indicated Occupant Density *(left)* and Effect of Normalized Demand on Price Growth *(right)*

6.6 Housing Policies

Presumably, a housing market with no outside stimulus would remain at some reasonable equilibrium, indefinitely. However, real world systems are never free of influences from external sources, and the Singapore Housing Market is no exception. One such exogenous variable, the population, has already been discussed. Housing policies, especially in Singapore where the government plays a strong participatory role in housing provision, are another major source of shock to housing markets.

6.6.1 Price Policy

Tu and Wong identified, through regression modeling, five monetary public housing policies implemented between 1993 and 1997 that contributed most significantly to the price bubble of the mid-nineties. The initial policies were directed at increasing the affordability of resale public housing, which had previously been out of reach for most households. After the initial policies had taken hold and the price began to skyrocket, the latter policies were implemented to dampen the frenzy of speculative demand.

Looking at the suite of policies as a single unit, rather than individually, we can see that the overall long-term effect was the increase of the mean Buyer Budget from 45 to 100, see Figure 6-12. The resulting price behavior is best understood as a period of exponential growth from the initial equilibrium price index of 45, subsequent overshoot to nearly 150, and damped oscillation to the new equilibrium price index of 100.

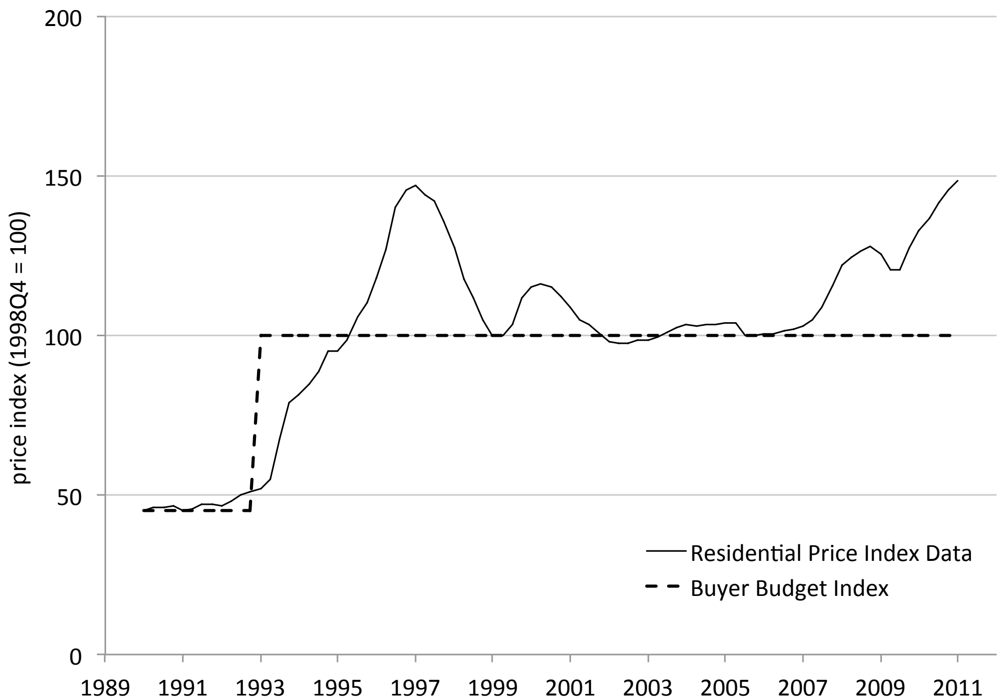

Figure 6-12: Actual Residential Price Index and presumed Buyer Budget Index

The generalized behavior and structure of this phenomenon, known as exponential growth with overshoot and oscillation, are shown in Figure 6-13. In the Singapore Housing Market Model, Price Index is the State of the System, Buyer Budget is the Carrying Capacity, and Affordability is the Resource Adequacy.

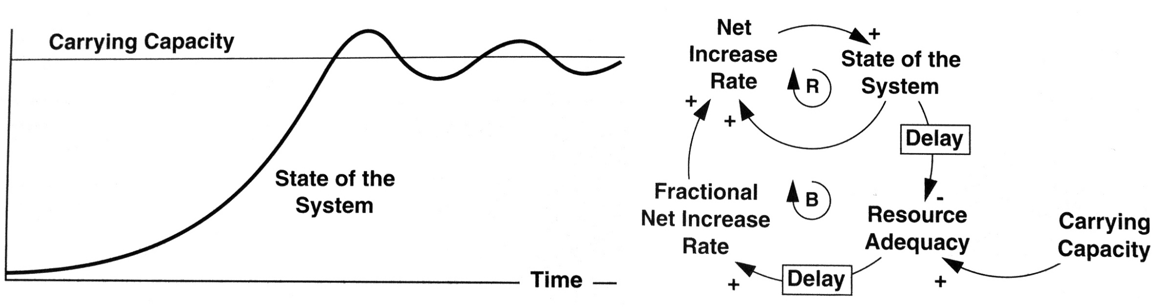

Figure 6-13: Reference mode and causal structure of exponential growth with overshoot and oscillation [64]

The reference price behavior from 1990 to 2006 can be explained by the overshoot and oscillation reference mode, but the single Buyer Budget increase in 1993 cannot explain the period of exponential price growth that begins around 2007. The current structure of the model does not endogenously generate this behavior. Rather, the modeled price continues its damped oscillation towards an eventual equilibrium of 100.

6.6.2 Supply Policy

Unlike the price bubble of 1996-7, which has been analyzed in a significant body of academic literature from the late 1990's and early 2000's [16, 75, 76, 77, 80, 66], coverage of the current price growth in residential markets has been limited to anecdotal and speculative assessments in the popular press:

> *...The HDB has ramped up the supply of new flats to meet demand and the market imbalance is showing signs of improvement...* [81]
>
> *...building Housing and Development Board (HDB) flats ahead of demand to ease the housing crunch...the MND is taking "active measures to address the temporary imbalance in supply and demand"...* [82]
>
> *...Another 3,000 applications were filed on Wendesday in the Housing Board's latest Sale of Balance Flats exercise, bringing the total number to 17,255 as at 5pm. With 2,874 balance flats for sale, the subscription rate for these so-called 'leftover' units is now six times...* [83]
>
> *...A property expert believes new immigrant arrivals will continue to support demand and prevent prices from falling in the wake of an impending flood of new flats onto the market...* [84]

One factor that appears in most explanations is reference to an overall shortage of housing. This is validated by the trend of residential occupant density, which has been increasing since 2003 and is now at its highest level since before 1990, see Figure 5-5.

Possible explanations for this increase in occupant density are rapid population growth, a shortfall in the stock of housing units, or both. After a period of little-to-no growth from 2002 to 2004, the population grew between 3.2% and 5.5% per year between 2006 and 2008, higher than the average annual growth of 2.6% over the modeled period but not enough, alone, to cause the observed price escalation, see Figure 6-14. The relative dearth of new unit initiations between 2000 and 2007 that resulted from stagnant real price growth is to blame for much of the housing shortage. Additionally, since 2007, a new suite of policies regarding the sublet of whole public units to non-residents appears to have amplified the current price increase.

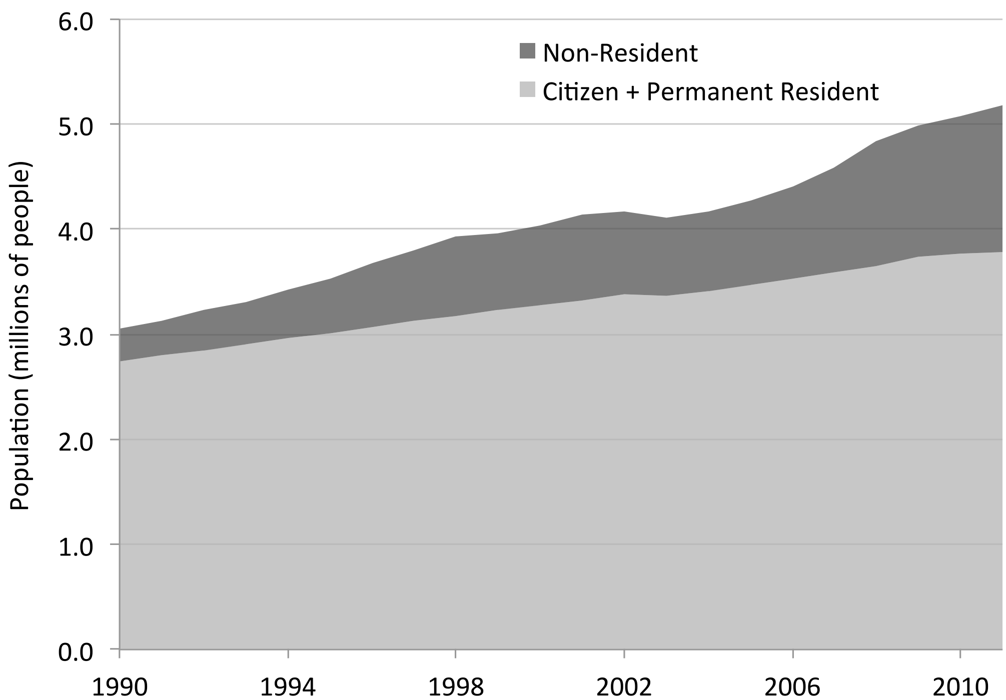

Figure 6-14: Singapore population breakdown: citizens + permanent residents, and non-residents

Prior to 2003, when citizens or permanent residents who owned public housing units purchased a new unit, private or public, they were required to immediately place their existing public unit on the resale market. This ensured that no person could own a public unit as a second home or as a rental unit.

Under the new policies, public units can be kept as investment or rental properties. Singaporean's who can now afford private housing or decide to consolidate multiple households into a single residential unit—by moving elderly parents back in with their children, for example—can retain their former public unit as an investment income property. Singapore non-residents, who are not qualified to own public housing, are allowed to sublet these whole public units from their citizen or permanent resident owners.

Historically, the HDB has sought to maintain a balance between public housing units available and the number of citizen and permanent resident occupant households seeking public housing. Private housing allocations are made to support citizens and permanent residents who can afford private units, as well as upper income non-residents also seeking to own private housing, see Figure 6-15.

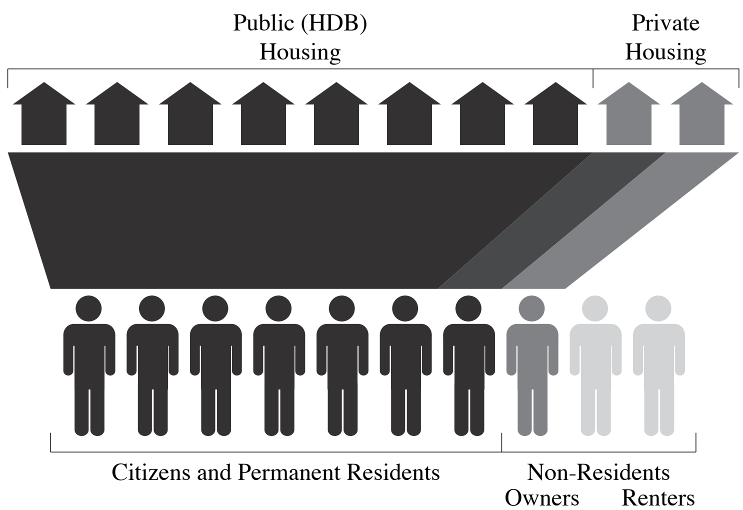

Figure 6-15: Citizen, permanent resident, and non-resident owner housing allocation

The remainder of the population, non-residents who can not afford to own private residences, have historically lived in a variety of informal housing arrangements: private rental units, bedroom sublets in citizen-owned public units, and employer provided worker dormitories, see Figure 6-16.

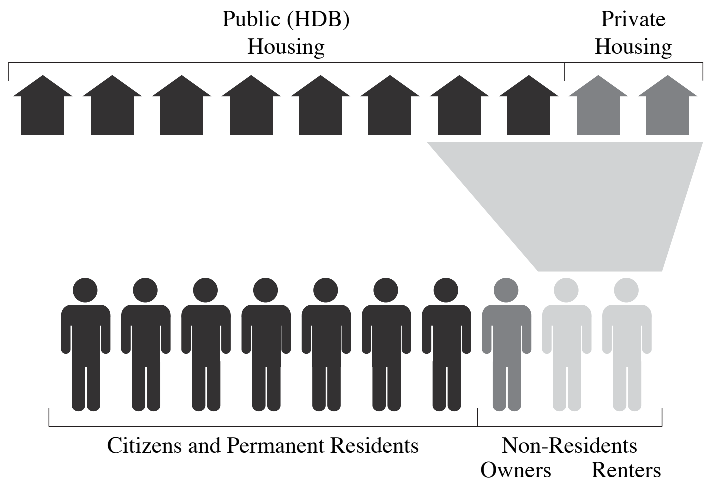

Figure 6-16: Non-resident renter housing allocation, pre-2007

Now, with citizens and permanent residents eligible to buy new units and keep their public units as investment and rental properties, the balance of supply and demand has been upset. The new, albeit small, fraction of public units being sublet to non-residents has effectively reduced the number of public units available for resale to prospective citizen and permanent resident owners, see Figure 6-17. While the provision of tens of thousands of high quality rental units for non-residents is a great benefit to the growing non-resident population, the result for prospective owners is a significant supply shortage that is driving prices up dramatically.

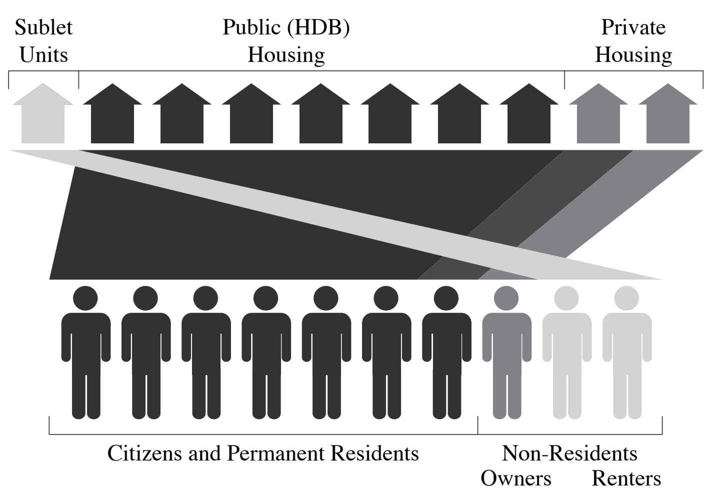

Figure 6-17: Non-resident renter housing allocation, 2007–present

Ultimately, at the core of the problem is a housing supply structure that is dedicated specifically to Singapore citizens and permanent residents. However, an aging population and low birth rates have meant very little natural growth in the citizen population [85]. The vast majority of Singapore's recent—and future—population growth is occurring in the non-resident subset of the population, through immigration. This growth, which is not fully accounted for in the current housing provision process, is exacerbating Singapore's housing supply shortage problem.

Table 6.1 shows the number of units approved for sublet between 2007 and 2011, as well as an assumed equal quantity of units being sublet without approval. As a policy input to the model, the indicated percentage of units is diverted from the for-ownership stock to a for-rental stock. This scenario produces growth in price and new unit initiation similar to that observed in the data, see Chapter 7 for model results.

Table 6.1: Public whole-unit sublet approval policy and assumptions, 2007–2011

Year	**Approved Sublets** *units/yr*	**Unapproved Sublets** *units/yr*	**Total Sublets** *units/yr*	**% of Stock** *%/yr*
2007	12,808	12,808	25,616	2.3%
2008	15,344	15,344	30,688	2.8%
2009	15,137	15,137	30,274	2.8%
2010	27,609	27,609	55,218	5.3%
2011	26,130	26,130	52,260	5.3%

As a result of skyrocketing prices, the government has announced and begun to implement a reversal of the large-scale subletting policies of the early 2000's. The possible effects these newest policies will have on the market are tested and discussed in Chapter 8.

Chapter 7

Policy & Residential Land Use: Results

Using the structure, inputs, and calibrated elasticities defined in Chapter 6 the results of the base case historical simulation from 1990 to 2011 are presented in the following sections.

As stated previously, the goal of this model is to reproduce the fundamental behavior trends exhibited by the reference data while keeping the model as simple and intuitive as possible, rather than minimizing absolute error. The specific behaviors observed in the data are exponential growth, overshoot, and damped oscillation. The results show that the calibrated model produces all of the desired behaviors, while closely following the actual price index value throughout the modeled period.

7.1 Model Results

Figure 7-1 shows the modeled Price Index in relation to the actual Price Index. The two implemented policies—a step in Buyer Budget from 45 to 100 in 1993, and a gradual transfer of for-ownership units to a for-sublet unit stock between 2007 and 2011—are responsible for the general behavior of the model.

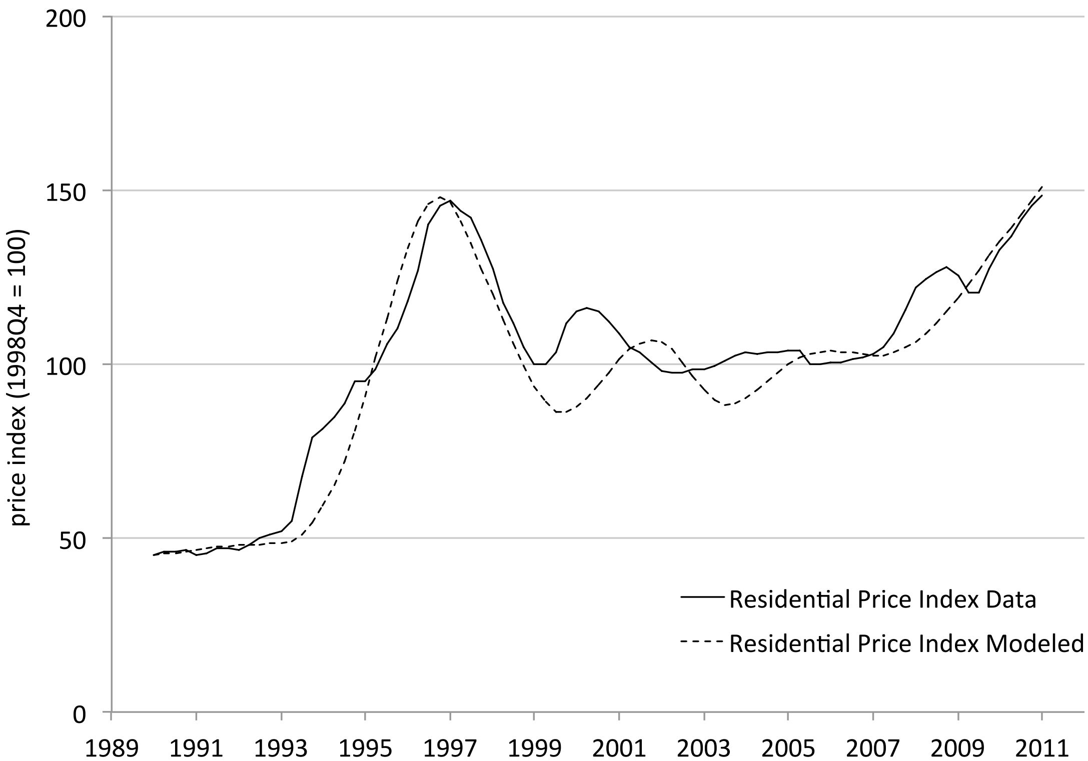

Figure 7-1: Actual versus modeled price index, 1990–2011

The first policy, which drastically increases affordability, creates tremendous demand for new and resale public units and results in a price explosion, with the price index growing by nearly 200% in four years. The delay between the initiation and completion of new units, and the lag in residents' adjustment of their desired occupant density lead to the extreme overshoot of the price index. As new supply finally comes online, and residents adjust their preferences about occupant density, the ratio of supply to demand inverts, and causes the price to fall drastically. The diminishing repetition of this cycle leads to a full decade of damped price oscillation.

The second policy, a reduction in for-ownership housing supply beginning in 2007 and increasing through 2011, paired with steadily increasing demand, is the cause of the recent period of price growth. Several possible scenarios of future price trend are examined in Chapter 8.

To verify that the structure of the model accurately represents the various interactions in the actual system, the model output must be verified for several critical variables. In the current model, price is ultimately determined by normalized demand, which is the ratio of the modeled unit demand to available supply of units. For this calculation to be meaningful, the modeled unit demand must be compared against the actual supply of units. In order for the supply of units to be correct, the initiation rate of new units must also be accurate, when compared with the data.

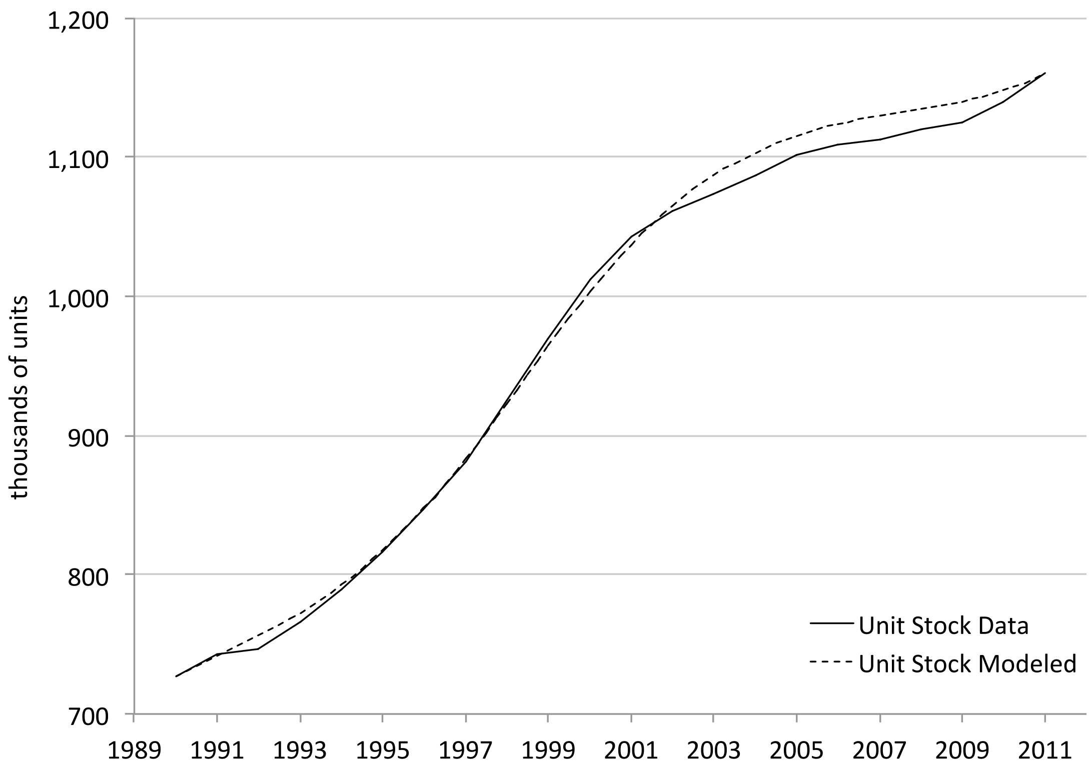

Figure 7-2: Actual versus modeled housing unit stock, 1990–2011

Figure 7-2 shows the modeled Unit Stock in relation to the actual Unit Stock, and Figure 7-3 shows the modeled Unit Initiation Rate in relation to the actual Unit Initiation Rate. The calibrated model produces both a unit stock and a new unit initiation rate very similar to the recorded values.

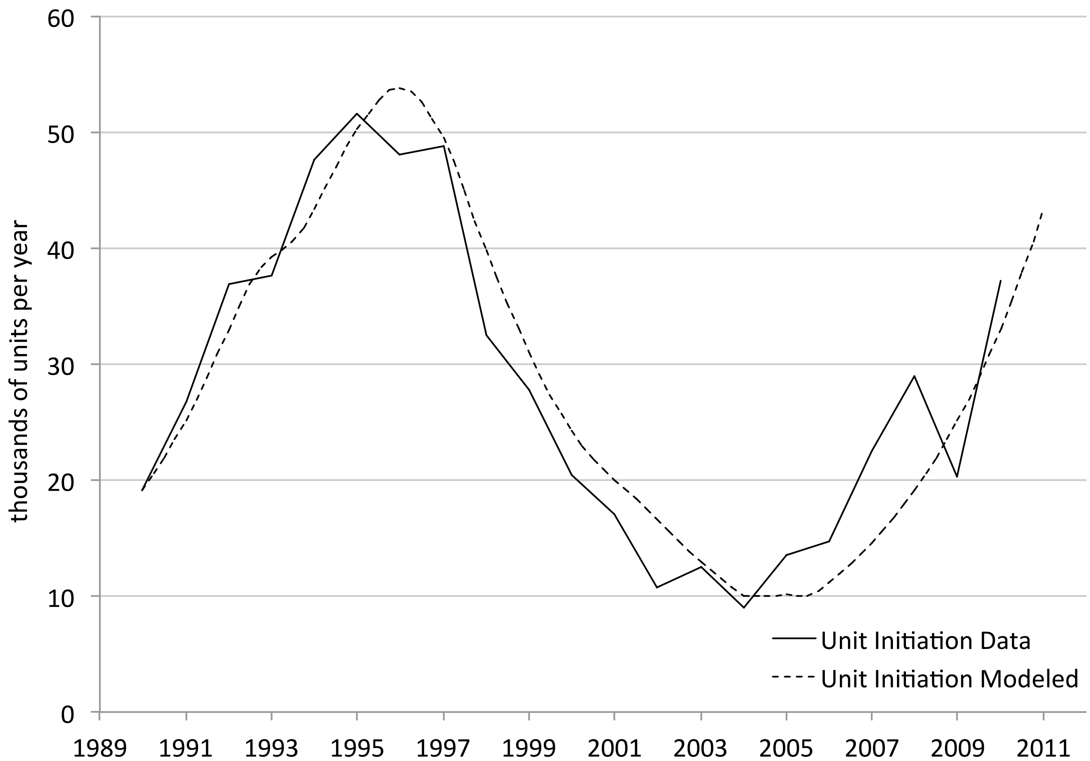

Figure 7-3: Actual versus modeled unit initiation rate, 1990–2011

The other driver of price, modeled unit demand, is ultimately a function of desired occupant density and actual occupant density. Desired occupant density is not a measured variable, so there is no reference data to compare it with. Rather, it is an inferred intermediate variable that expresses the changing desires of the population to adjust their living situations as a result of housing prices. With some delay—1.5 years, after calibration—residents adjust their desired occupant density downward when affordability is greater than 1, meaning housing is relatively affordable, and they adjust their desired occupant density upward when affordability is less than 1, when housing is unaffordable.

When the desired occupant density is lower than the actual occupant density, the current stock of units is insufficient to meet the desired demand, and the price increases. When the desired occupant density is greater than the actual occupant density, the unit supply is more than sufficient, and the price falls. Because of the significant lags in the new unit supply chain and the desired occupant density, oscillation results from any shock to the supply, demand, or price of housing. Figure 7-4 shows the modeled Desired Occupant Density in relation to the modeled Actual Occupant Density.

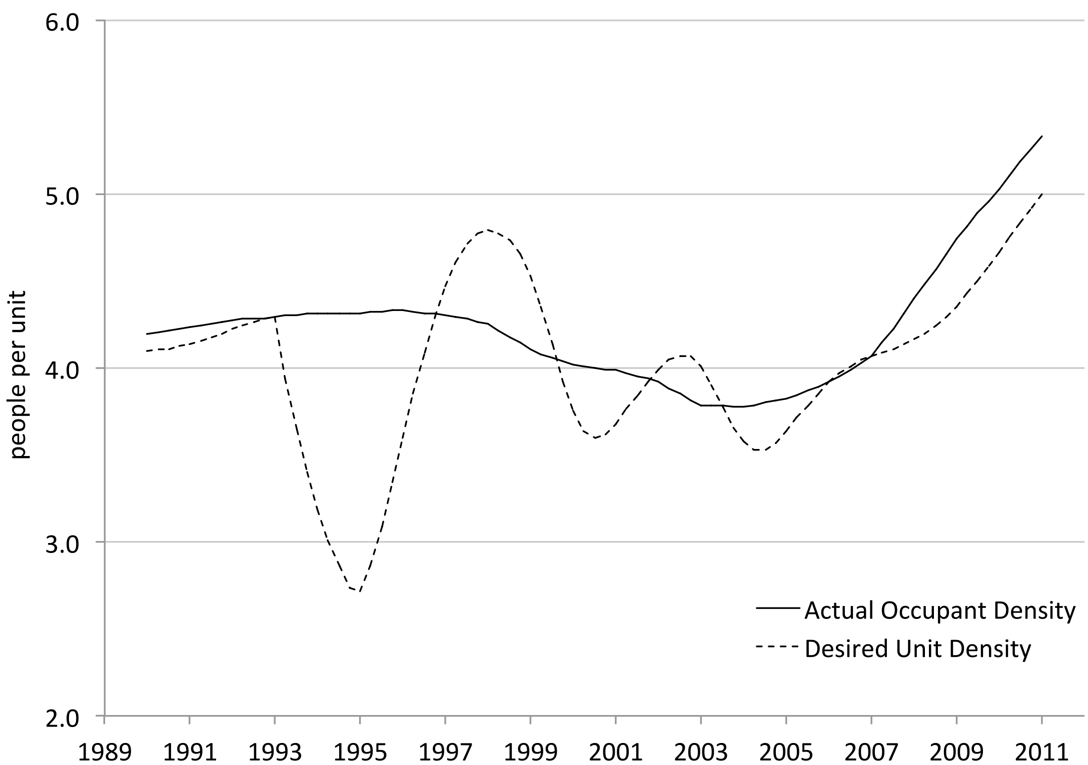

Figure 7-4: Actual occupant density versus modeled desired occupant density, 1990–2011

Chapter 8 discusses the implications of the modeled policies, possible alternatives that could have been implemented, and what effects the current and future whole-unit subletting policies might have on the trend in price and housing unit provision moving forward.

Chapter 8

Policy & Residential Land Use: Discussion

The simple System Dynamics model formulated for this study is founded on two seminal structures for modeling commodities and managing a stock. With relatively few variables and little exogenous data it is able to simulate the general trends of Singapore's residential price index and the dynamics of the housing stock quite closely over a 20 year period. The model also demonstrates the ability to test the effects of different policy types, incorporating both demand-side (affordability) and supply-side (whole unit sublet) policies to generate the observed historical behavior.

The next step is to extend the time period for the baseline model and test assumptions about future population and modifications to policies regarding whole-unit subletting to see what range of possible future paths the housing market might take.

8.1 Baseline Historical Simulation

The baseline historical simulation reproduces the two observed trends in price: exponential growth, and overshoot with oscillation. Given that the fundamental structure of the model is two balancing feedback loops, this behavior may at first seem non-intuitive. However, on closer inspection there are two major factors that account for the generation of this behavior.

First, exponential growth is typically generated by a reinforcing feedback loop, see Subsection 2.5.5. Integrated into the price formation structure, there is one subtle reinforcing feedback loop in the model, identified in Figure 6-13, that allows the model to generate exponential growth. Price is modeled as a stock in the model, and the price grows (or decays) at a ‘normal’ rate modified by the influence of normalized demand on price. When normalized demand is high the price grows at a faster rate. As normalized demand falls, the price either grows at a slower rate or decays.

There are two distinct periods of exponential growth in price over the modeled period. Between 1993 and 1997 the price grows exponentially at an average of 29% per year. This growth was the result of increased affordability from the favorable lending policies instituted by the HDB to promote resale purchases. Increased affordability meant that occupants could afford to live less densely, and so the demand for units increased. From 2007 to the present a shortage of unit supply has accounted for the 10% annual price growth. Although through different mechanisms—increased unit demand and decreased unit supply—these two policies have both served to increase normalized demand, which in turn has raised the fractional price growth rate and caused periods of sustained exponential growth.

The second, and perhaps more interesting trend observed in the historical price is persistent oscillation. Oscillation is a more complex dynamic than exponential growth, but is generally the result of delays in the system. Delays can be physical or informational. In the housing market model there is a physical delay between the desired initiation rate and the actual initiation capacity achievable by the construction industry due to the time it takes to acquire or dispose of labor. There is a physical delay of nearly three years between new unit initiations and their completion. Also, there is a key informational delay between changes in price and peoples’ desires about how densely to live.

These various delays act in a way to induce and perpetuate oscillation in the system. One example of how this oscillation occurs is evident around the price peak of 1997. Driven by aggressive affordability policy, housing demand and prices grew tremendously over the period from 1993 to 1997 . To meet this demand, the construction industry ramped up its size and output, initiating more units every year, however not fast enough to keep up with demand. The lag between quickly growing demand and the slower increase of new unit supply resulted in a temporary 'shortage' of supply, which caused the price to continue to grow well above the level of average affordability. This overshoot represents the first deviation from the equilibrium price that ultimately lead to future oscillation.

With the price skyrocketing, 1995-1997 were the three biggest years in new unit initiations in Singapore's history. By 1997, the completion rate of new units had caught up to the growing demand and the price had climbed so high that consumer confidence in price growth was overshadowed by the pure inability of buyers to afford such expensive units. Demand began to wane, and when the price peaked that year, 120,000 new housing units were under construction, also a historical high. Despite the fact that both price and demand would fall for the next two years, most of these housing units were carried through to completion. This flood of unwanted supply further depressed housing prices. In 1999, when the price began to level off and most of the excess units had been purchased, the construction industry was roughly half the size it was at its peak. At this point, low prices began to entice buyers back into the market. Unfortunately, the construction industry was so hard hit by the housing collapse that it would take several years to recover and bring new units online to satisfy the new demand. So, with another shortage of supply, the price began to climb again. This cycle of unit supply lagging behind buyer demand continued for nearly a decade, dampening slightly with each cycle.

The delays identified in the Singapore housing market are common to all major housing markets and lead to persistent and frustrating oscillation, known as real estate cycles, in nearly every case. In fact, as early as 1970 Meadows identified the delays operating within and between supply chains and consumer demand as the source of oscillation and volatility in all commodity markets [79]. Quantitative modeling gives insight into the effect of past and future policies, as well as increasing overall understanding of these systems.

8.2 Future Projection

Now that the Singapore housing market model is calibrated and adequately reproducing historical trends, it can be used to project the trends of price, unit initiation, unit stock and occupant density into the near future. As with the historical simulation, the intention here is not to accurately predict point values of any of the particular indicators at a specific time in the future. Rather, the goal is to understand what general effects various policies might have on future trends. For example, given the current policy landscape should prices begin to level in the near future or continue to grow? Will the size of the construction industry begin to level off or continue to oscillate as it has in the past?

In order to answer these questions, assumptions must first be made about the model's exogenous input values in the future. All of the model parameters are kept constant between 1990 and 2011, so no changes will be made for future projections. The current formulation of the model has only one exogenous data stream, the total Singapore population. Figure 8-1 shows the historical population from 1990–2011.

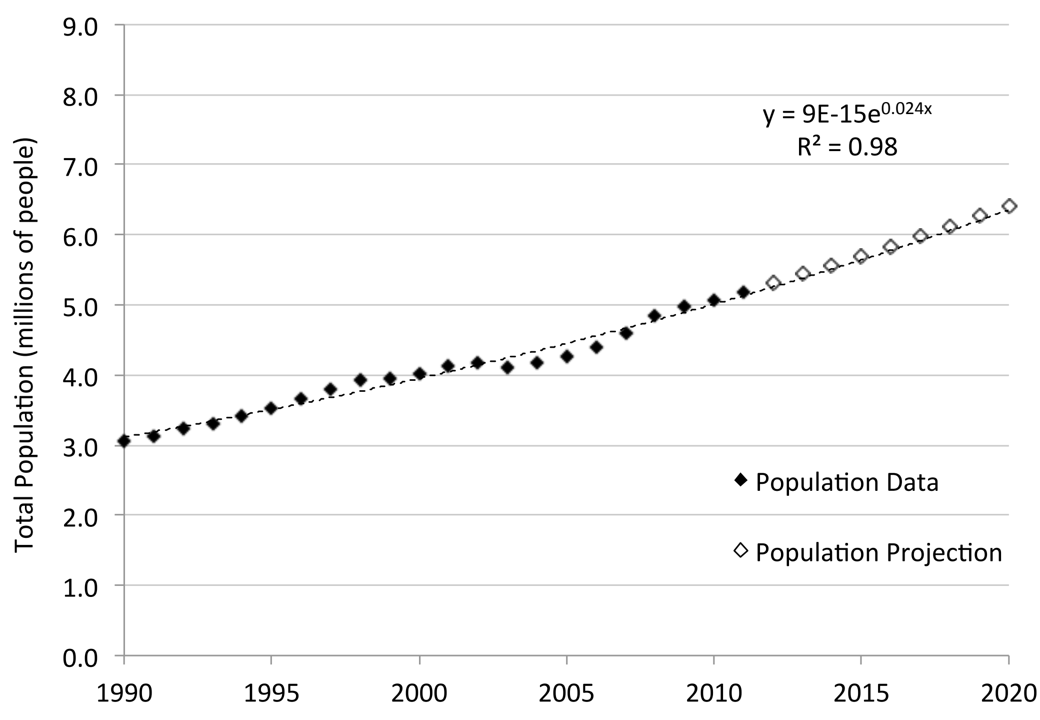

Figure 8-1: Population projection for policy scenarios, growth rate = 2.4% per year

The dashed line is an exponential regression of the historical data, and has an R^2 value of 0.98, which is a very high degree of fit. The regression line has an exponential growth rate of 2.4% per year, and is projected 10 years into the future for reference. The population projection is based on the final population data point, 2011, which is increased by the same 2.4% per year through 2020 to a final population of 6.4 million.

8.3 Housing Policy Scenarios

Three near-term policy scenarios are described and evaluated in this section using the 'normal' population growth projection from Section 8.2, and are summarized in Table 8.1.

The first policy, *Reduce Sublet*, is considered to be the default policy, because it is the most likely future course of action. This policy calls for immediate reversal of the policies allowing whole-unit subletting of public units. Over the next two years, all of the units in the for-rental stock will be returned to the for-ownership stock, increasing the supply of resale units available while dramatically reducing the dedicated housing stock for non-residents. This policy appears to be the direction the Singapore government is headed, having already significantly reduced the allowance for whole-unit sublets through an extension of the Minimum Occupancy Period (MOP) required before whole-unit sublets are allowed from 3 to 5 years [18]. Since average ownership of HDB flats is only about 7 years, this greatly reduces the number of HDB flats eligible for whole-unit subletting [15].

The second policy, *Increase Subsidy*, is a modification of the reduce sublet policy. It would also immediately reduce the stock of whole-unit sublets over the next two years. But as this policy will bring a huge supply of units back into the resale market, it is anticipated that it will also cause a significant drop in housing prices. While this is a benefit to those interested buyers who cannot afford the current elevated prices, it would also mean significant equity losses for all those who purchased housing in the last four years. As the Singapore government has long championed home ownership as a safe investment vehicle for retirement, it would be in the government's best interest to prevent prices from falling dramatically as a result of new policies. In order to prevent a price drop, the government could again increase housing subsidies to make housing affordable to new owners at the current prices. This scenario tests an increase of buyer budget by 50% through demand policies, see Table 5.1. The obvious downside to this type of policy is a direct financial burden on the Singapore government, which makes this a highly unlikely scenario, however it is worth seeing what the hypothetical effect might be.

The third policy, *Continue Sublet*, would retain the current assumed fraction of units dedicated to whole-unit sublets at its current level, 18.5% of the total stock. Rather than returning the whole-unit sublets to the for-ownership stock, they would be maintained as a permanent supply of housing for non-residents, and the construction industry would be given the task of meeting the current demand through new unit construction. The obvious benefits of this policy would be the establishment of a permanent sector of rental housing, owned by Singapore citizens and permanent residents, regulated by the Singapore government, and dedicated to housing the ever growing non-resident population.

These policies were chosen for their extreme polarity, so that the resulting trends would be distinct. If a new policy were to be crafted for the future, any optimal hybridization of the policies proposed would be possible.

Table 8.1: Future Singapore housing policy scenario summary, 2011–2020

Policy	**Whole-Unit Sublets** *supply policy*	**Financial Subsidy** *demand policy*
Reduce Sublet	Reduce whole-unit sublets to zero in 2 years	none
Increase Subsidy	Reduce whole-unit sublets to zero in 2 years	Increase average buyer budget by 50%
Continue Sublet	Maintain whole-unit sublets at 18.5% of total stock	none

8.3.1 Policy Scenario Results

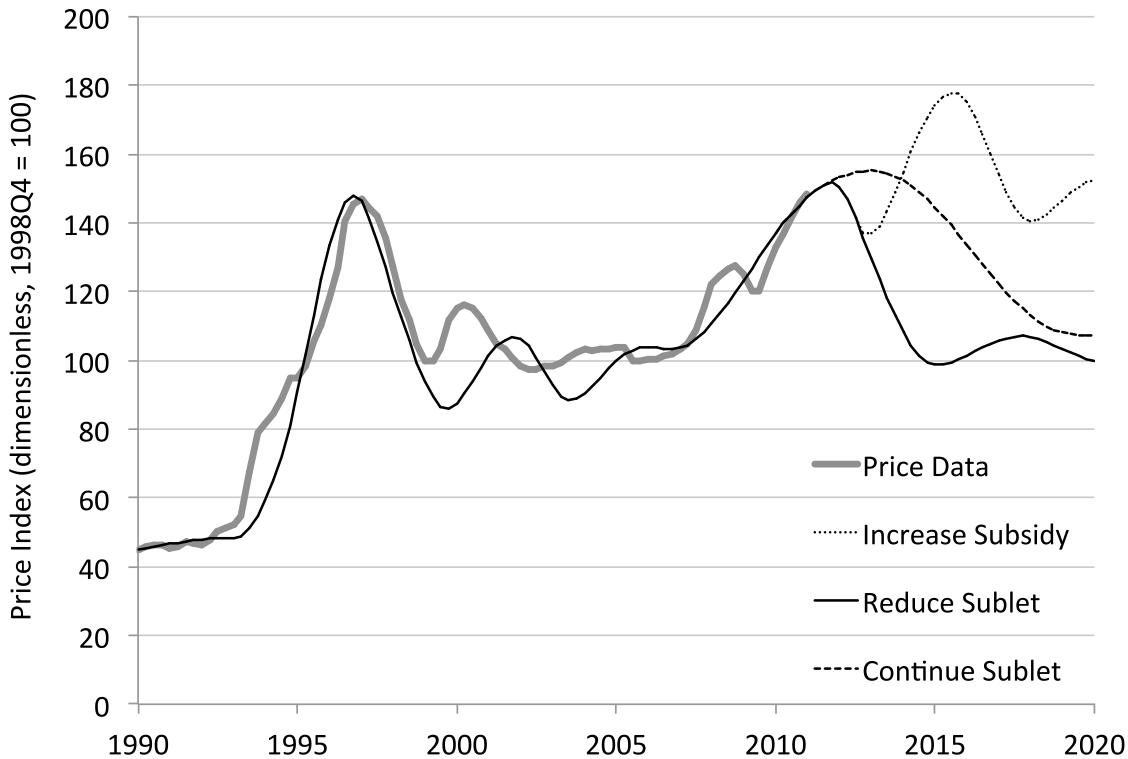

Figure 8-2: Future price projections of housing policy scenarios

As expected, the default policy, *Reduce Sublet*, leads to a rapid short-term price decline. This is the result of a near instantaneous flooding of the resale market with a huge supply of recaptured whole-unit sublet units. The *Increase Subsidy* policy, which also returns all of the whole-unit sublets to the for-ownership stock, maintains a higher price despite the relative oversupply. This is because the new increase in affordability allows more people to afford units at the current elevated prices, so maintains a higher overall demand that keeps price high. As with the demand policies of the mid-1990s, the increase in subsidy also results in significant oscillation as the construction industry lags behind the demand generated by an instant boost in affordability. Finally, the *Continue Sublet* policy shows a similar decline in prices back toward the equilibrium price index of 100, however the change is much more gradual, and demonstrates significantly less pronounced oscillation than the other two, more dramatic policies.

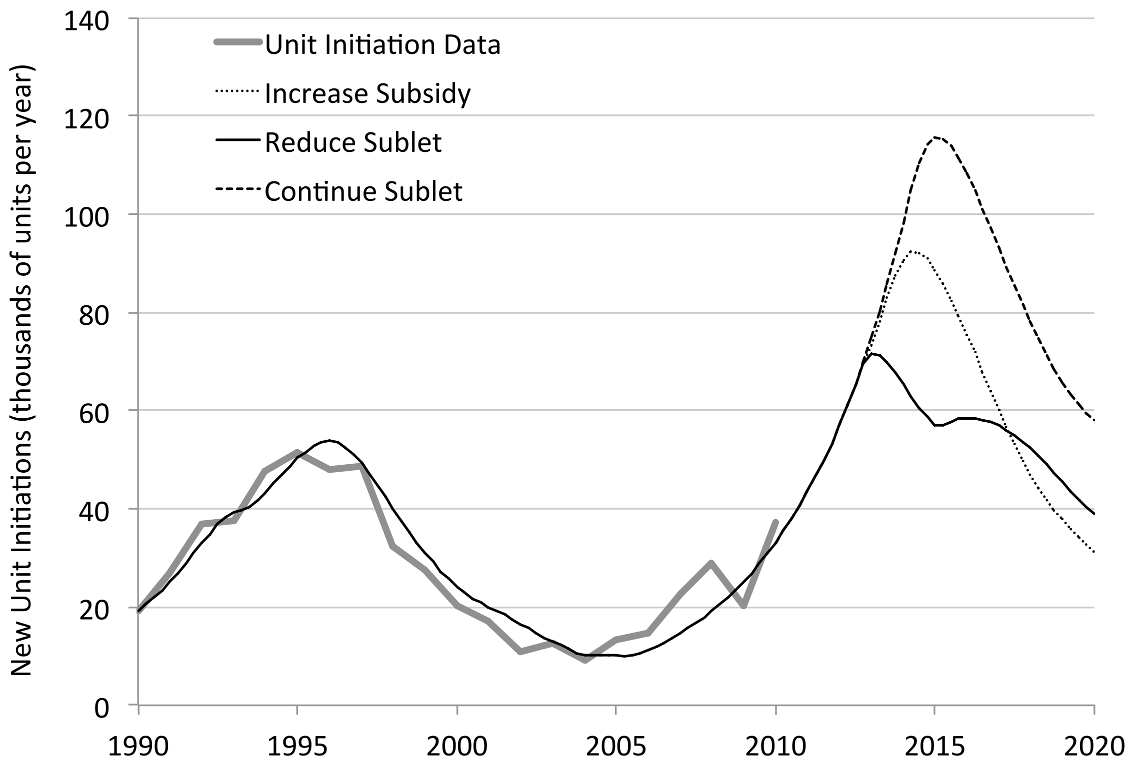

Figure 8-3: Future unit initiation projections of housing policy scenarios

Regardless of the which policy is enacted, the model shows that new unit initiation will continue to increase significantly in the near future. This is largely a consequence of the slump in new housing starts in the first decade of the millennium.

The *Reduce Sublet* policy has the least pronounced effect on new unit initiations. This is because most of the current housing shortage will be met by units that are already built shifting from sublease to new ownership, which is a much faster means for increasing supply than building entirely new units. Unfortunately, by dissolving this supply of rental housing, a huge population of non-residents will be left without adequate housing arrangements, once again. Because the non-resident population is the fastest growing segment of the Singapore population, their housing needs must eventually be addressed in a formal way, and the current policy direction appears to undercut that effort.

The *Increase Subsidy* policy has a more pronounced effect on new unit starts. Even though the same supply of whole-unit sublets will be returned to the resale market, by increasing subsidies the overall demand will grow too, as more and more households will be able to afford to buy. So, in addition to the shift of rental units, significant new unit supply will be needed to satisfy the high demand.

Finally, the *Continue Sublet* policy has the greatest near-term effect on new unit initiation volatility. Because no existing units are returned to the resale supply in this scenario, all future demand for units must be met through new construction. This policy does, however, address the non-resident population by maintaining a significant supply of rental housing specifically for that segment of the population. So, while in the short term this policy will require greater construction rates, it will also be establishing a more sustainable future housing distribution than either of the two previous policies.

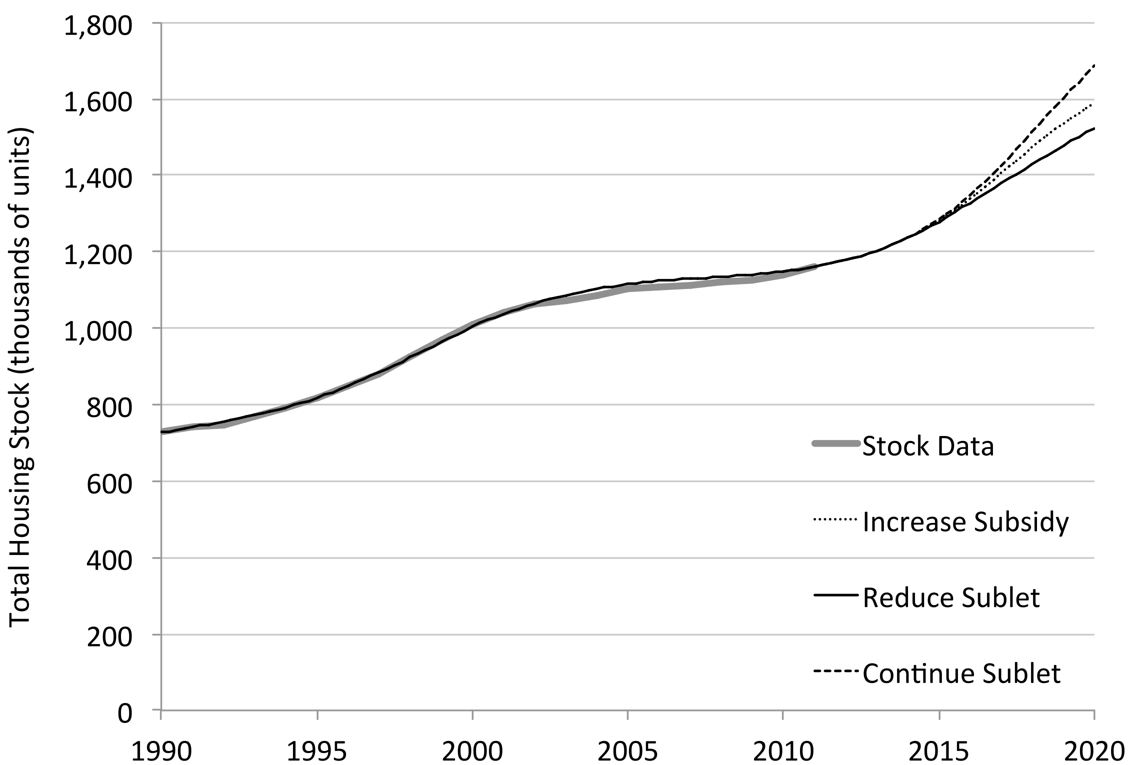

Figure 8-4: Future unit stock projections of housing policy scenarios

Merely the accumulated effect of new unit initiations, the *Reduce Sublet* policy results in the smallest future housing stock, the *Increase Subsidy* policy in a slightly larger stock, and the *Continue Sublet* policy in the greatest overall housing stock.

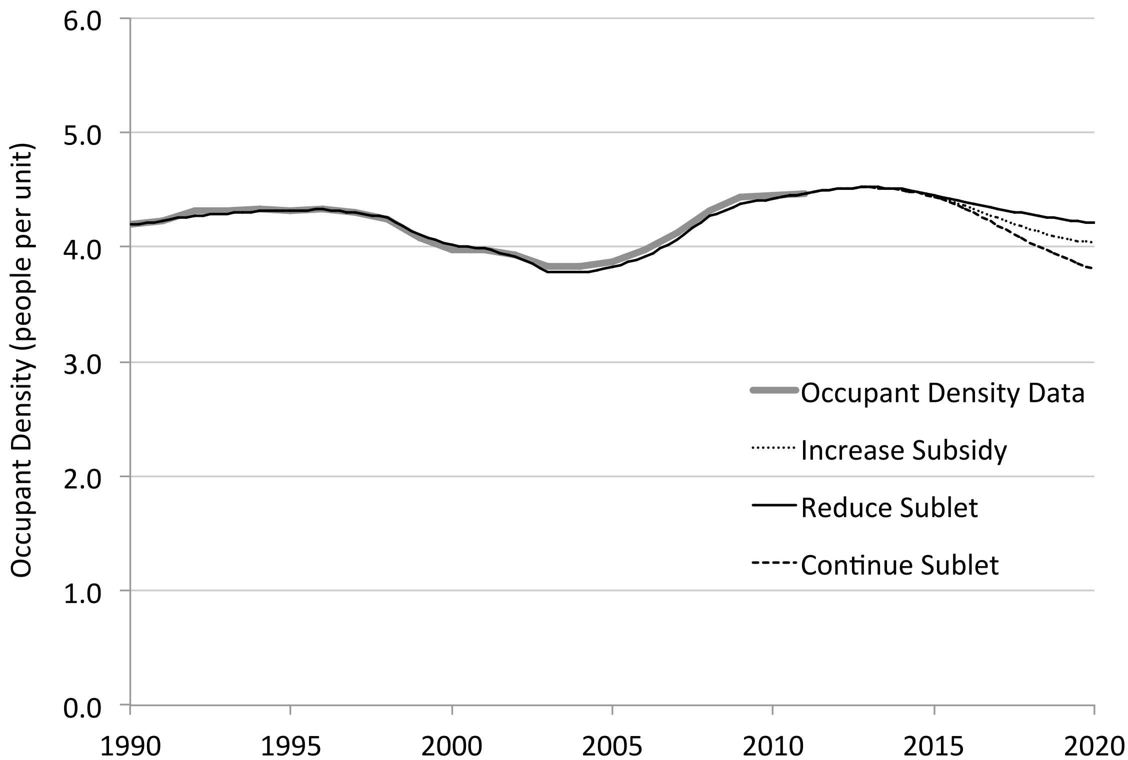

Figure 8-5: Future occupant density projections of housing policy scenarios

Since the population in all three scenarios is the same, the unit stock translates directly into occupant density, which shows a similar trend. The *Reduce Sublet* policy has only a slight effect on occupant density, which is an indicator of the neglected non-resident population. The *Increase Subsidy* policy has a moderate effect, in this case returning the occupant density to roughly its average value over the whole modeled period. Again, though, this policy neglects the non-resident population so the occupant density actually represents the average of two populations: citizens and permanent residents living at low occupant densities in a large housing stock, and non-residents crowded into inadequate facilities. Finally, the result of the highest construction rates from the *Continue Sublet* policy is a uniformly low occupant density that gives adequate accommodation to residents and non-residents alike.

Overall, the *Reduce Sublet* policy has the most immediate stabilizing influence on all indicators. Price should fall quickly, new unit initiations should not increase too significantly, the overall unit stock will remain modest, and the occupant density will fall very gradually. While this policy may be the most resource efficient, as it requires the least growth in the housing stock, it will likely not satisfy the growing non-resident population in the long-term, and could require significant future adjustments. The *Increase Subsidy* policy is not very practical due to its high costs, and its effects are not the most beneficial in any area, so it is probably not a policy worth considering further. Finally, the *Continue Sublet* policy represents both the best and worst simulated future. It is the worst because it will require a virtual explosion of the construction industry to meet short-term demand. However, once the new unit supply is established, this is the only policy that fully accounts for the non-resident population's housing demand. And given the trend of growth in that population group, it is one that cannot be ignored for long. After a brief destabilization, the *Continue Sublet* policy offers a path to a more sustainable and better managed housing future for Singapore.

8.4 Population Scenarios

Given that neither the *Increase Subsidy* nor the *Continue Sublet* are likely to be chosen as the future policy regarding whole-unit subletting in Singapore, this section will focus on the most likely scenario, *Reduce Sublet*, to test the effect of three varying population futures: low, normal, and high growth rate.

As stated in Section 8.2 the normal projected population growth over the next decade would be roughly 2.4% per year. The low growth scenario will test half the normal population growth rate, 1.2% per year, and the high growth rate scenario will consider double the normal rate, 4.8% per year. Figure 8-6 shows the historical population and the three projected scenarios. The low projection gives a final population of about 5.8 million, the normal projected population is 6.4 million, and the high projection ends with a population of 7.9 million people.

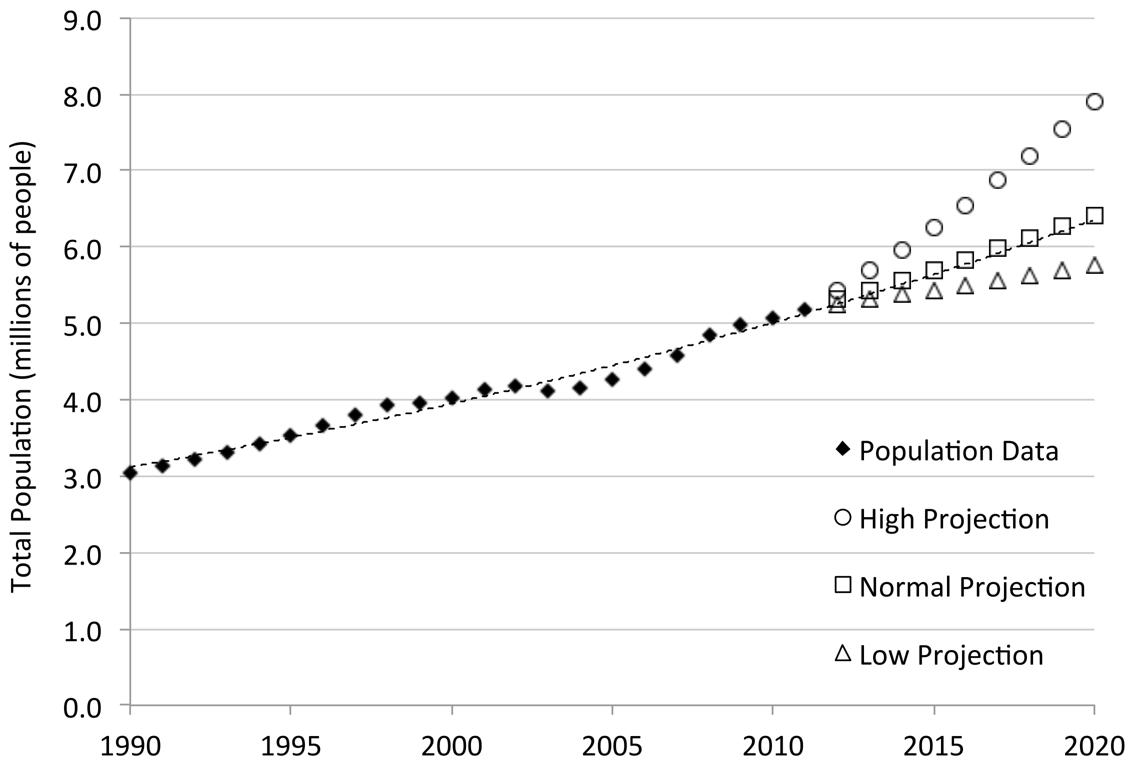

Figure 8-6: Future population projection scenarios: High (4.8% per year), Normal (2.4% per year), and Low (1.2% per year) growth rates

8.4.1 Population Scenario Results

Figure 8-7 compares the high and low growth variations with the default normal growth scenario. Interestingly, the high population growth scenario has the best effect on the future price trend of the *Reduce Sublet* policy. This is because, despite the rush of former sublet units returning to the resale market, growing population means growing demand, which maintains an elevated price longer. A slower return to the equilibrium price is better for overall market stability than an abrupt drop in price. Conversely, the low population growth scenario combines the new increased supply of resale units with a decreased demand, both of which serve to lower price. The low growth scenario also shows undershoot, with the price passing below the equilibrium price of 100 before rebounding with significant oscillation. Counter to intuition, despite a relative housing shortage, the model suggests an immediate decrease in population growth rate would not necessarily improve future market conditions.

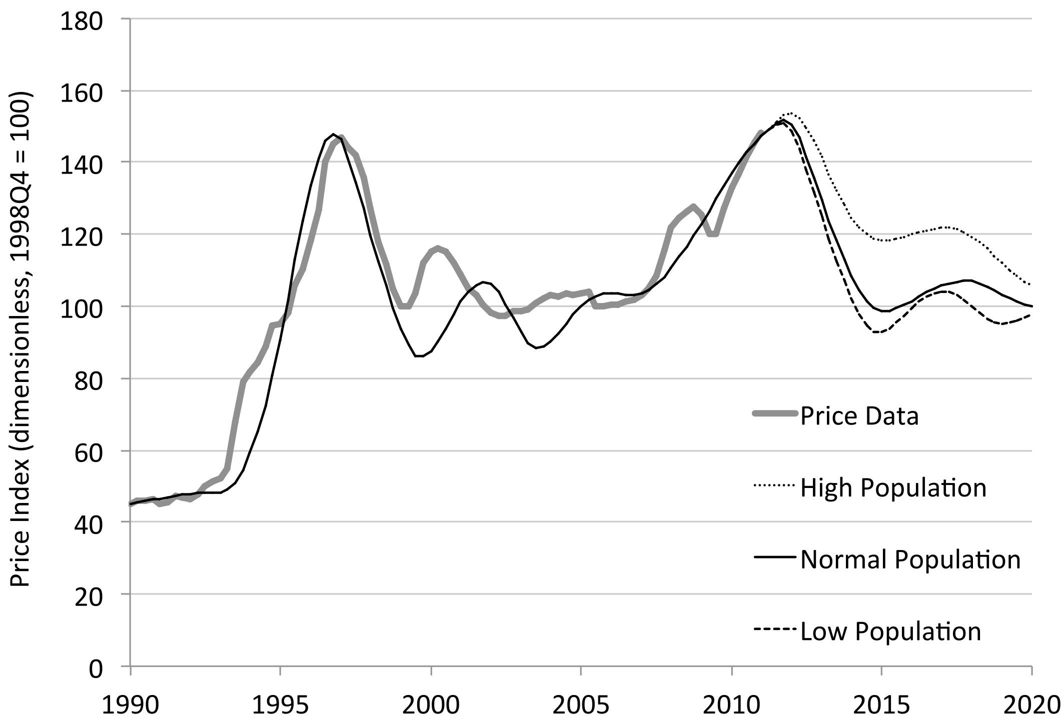

Figure 8-7: Future price projections of population growth scenarios

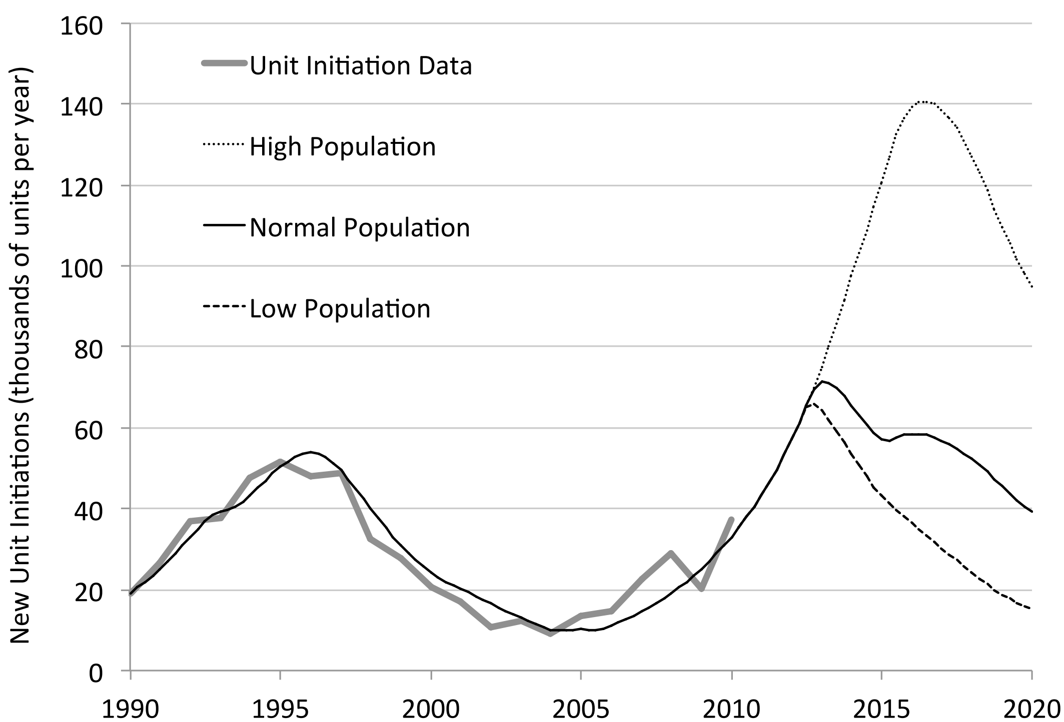

Figure 8-8: Future unit initiation rate projections of population growth scenarios

While a high population growth future has a long-term stabilizing effect on price, it has the worst short-term implications for new unit initiations, which would need to more than triple from current rates to meet the explosion of demand brought on by a ballooning population, see Figure 8-8. In contrast, the low population growth scenario requires only modest additions to the unit stock, and would demand the least immediate growth, also resulting in the less future contraction of the construction industry over the next decade.

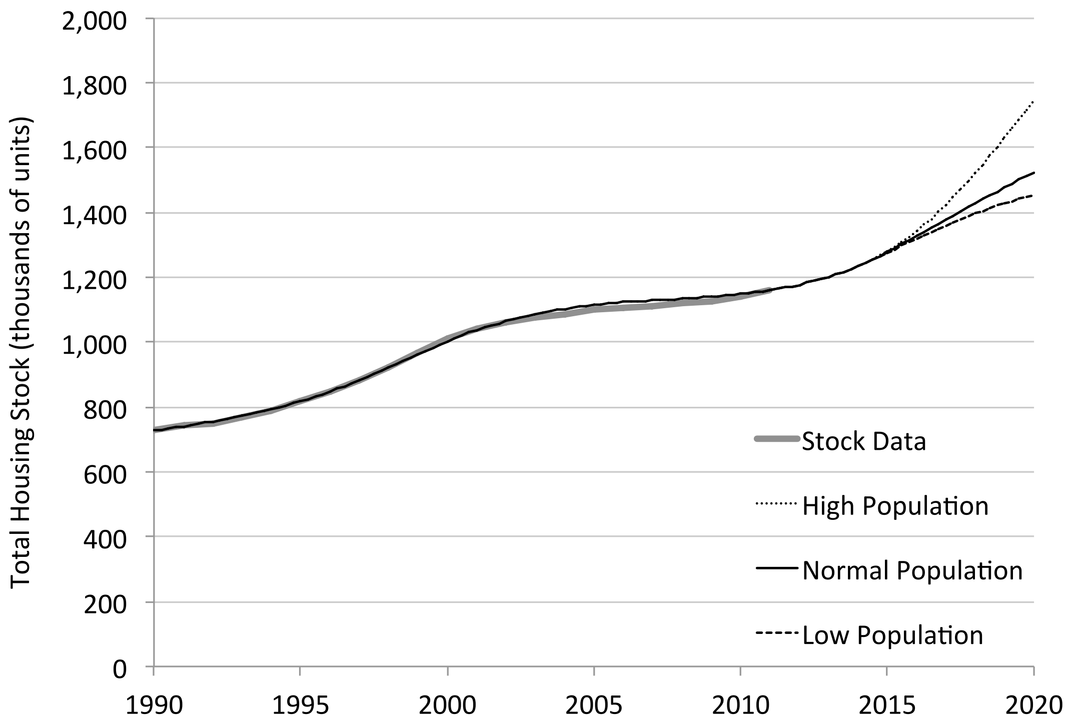

Figure 8-9: Future unit stock projections of population growth scenarios

Again, new unit initiations accumulate in the housing unit stock, which would grow to nearly 1.75 million in the high growth rate scenario, compared to the more modest growth of the normal and low population scenarios. The results presented in Chapter 4 show a maximum future growth potential of roughly 825,000 new housing units given the current residential land allotment, which would yield a total unit stock of 1.99 million units. The high growth scenario would put Singapore's future residential land allotment at nearly full capacity in just 10 years.

Finally, despite tremendous growth in new unit initiation, the high growth popu-

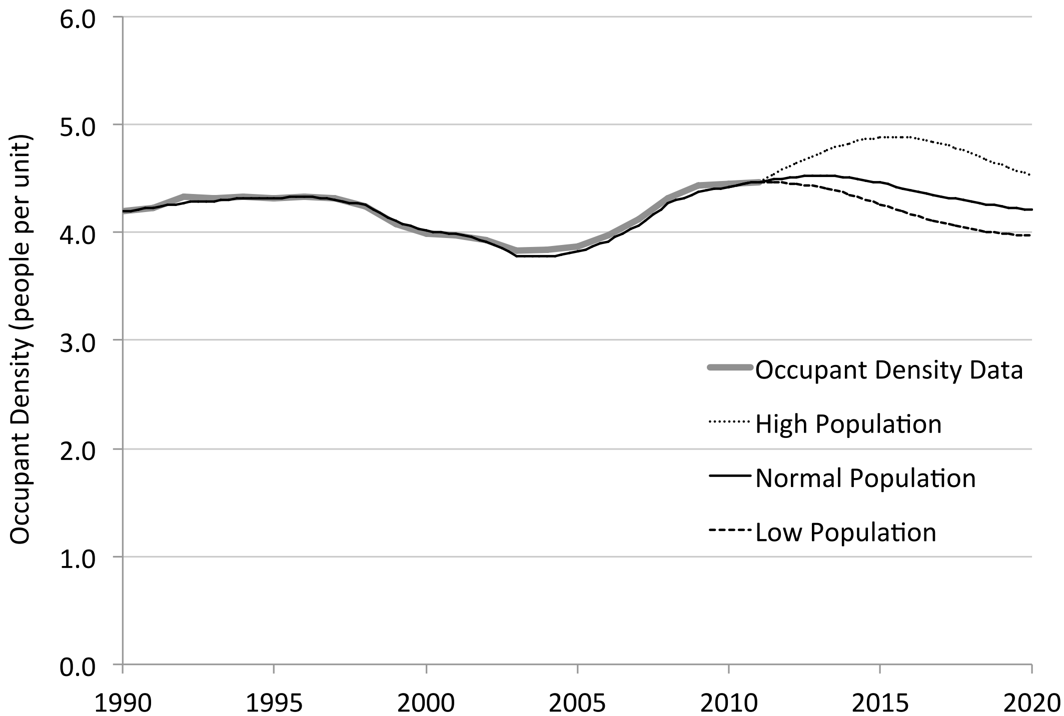

Figure 8-10: Future occupant density projections of population growth scenarios

lation scenario would result in a significant, long-term increase in occupant density. Since occupant density is a proxy for the population's satisfaction with the available housing stock, it is inferred that a high growth population scenario would have a strong negative effect on overall contentment within the population. Conversely, a low population growth scenario would bring the occupant density down to a level that would likely suit most residents and non-residents.

While slow population growth does alleviate some of the problems caused by the present housing shortage, it would almost certainly have knock-on effects to other sectors of Singapore's economy. This study does not attempt to quantify those effects. It can be stated, however, that *where* the future population growth occurs will have a strong effect on how efficiently that population is housed by the HDB and URA. Given the current model for housing provision, growth or decline in the citizen and permanent-resident population are closely monitored and planned for in future housing allocations. Changes in the non-resident population are not fully accounted for because no single, dedicated stock of housing is allocated to this population. Although the current attitude of the Singapore government is to spur natural growth within the citizen and permanent resident population, adapting current housing provision methods to better account for non-residents would provide greater future flexibility in a wide range of population growth scenarios, both natural and immigration-based.

Chapter 9

Conclusions

It is clear from the results of this study that Singapore's long-term planning and policy approach to housing has put the nation in an advantageous position for handling future growth, changes in development patterns, trends in increasing wealth, and the demands of an aging population. By maintaining government ownership of most residential land, and by directly controlling the housing stock through government land sales—which are in fact long-term leases—and public housing provision, the Singapore government is able to adjust the course of housing trends through new construction and redevelopment.

Given the 2008 Masterplan's zoned residential land area of 12,890 hectares, roughly one third of the total allotted residential land is still available for future development, enough to accommodate a population growth of 2.3–3.3 million people. Also, the mean residential redevelopment time is currently 11.2 years, meaning a typical residential lot in Singapore could be redeveloped to suit changing housing needs in slightly more than a decade.

Despite the strategic position of future housing in Singapore, there is considerable dissatisfaction with current housing prices and availability among citizens and permanent residents. In the last eight years, the average residential occupant density has increased from 3.85 to 4.45 people per housing unit. This increase of nearly 15%, the result of a housing supply shortage, has dramatically raised the price of housing, which has experienced 50% real growth in the last five years.

9.1 Policy Evaluation and Future Housing Provision

The Singapore Housing Market System Dynamics model, built to simulate housing prices and the supply chain, reproduces the price trend over the last two decades using only the commodity principles of supply and demand, and exogenous inputs of population and two key housing policies: increased affordability policy in the mid 1990s, and the introduction of whole-unit sublets of public housing in the early 2000s.

Further, when projected into the future, the model shows the impacts of reduced subletting, continued subletting, and additional price subsidies on housing prices and unit initiations over the next decade.

The policy projection results show that reduced subletting, which is the current course of action, will decrease real prices sharply and require the smallest increase in new unit initiation, while continuing to ignore the housing demands of non-resident renters.

Conversely, continued subletting would directly address the needs of non-residents by providing them an affordable, government managed stock of rental housing. But this would come at the cost of significant growth in new unit initiations, and a protracted return to stabilized prices.

Increased housing subsidy, an unlikely and expensive policy, is shown to maintain the current price, albeit with significant short-term oscillation. This approach would require more new unit initiations than the reduced sublet policy, but less than the continued subletting scenario. Still, this policy would come at the cost of non-resident housing provision, as it would return all whole-unit sublets to the for-ownership stock.

Finally, future population growth scenarios were tested, intuitively showing that slow growth has the the most advantageous effect on price stabilization and new unit initiation, while a high growth rate extends the return to past prices and requires tremendous growth in new unit starts. Because the core issue is a shortage of housing, higher future populations only serve to exacerbate the problem, while slower growth gives the construction industry a chance to catch up on the housing shortfall.

It is proposed that the lack of formalized housing provision for non-residents is the ultimate driver of the current housing shortage. Historically, as a very small fraction of the total population, non-residents were easily accommodated in surplus rental rooms, worker dormitories, and private rental apartments. However, as the non-resident population has grown to over 25% of the total population, this informal housing arrangement is no longer satisfying demand. Given Singapore's low birth rate and desire to continue to grow its population, the trend toward a larger non-resident population is likely to continue. While Singapore's exact non-resident housing allocation strategy is not publicly available for review, this study shows significant evidence that the housing needs of non-residents are not being fully met, and are leading to greater problems in the public and private ownership housing markets. One proposed solution would be to establish a new segment of rental housing specifically for lower-income non-residents, with the ultimate supply allocated based on the projected non-resident population, rather than perceived demand or prices in the public or private market.

Ultimately, how the Singapore government responds to the needs of the non-resident population will greatly influence the stability and success of housing in the future. But further, it will set the tone for how the country moves forward as a whole. To continue to satisfy the demands of the citizen population at the expense of new arrivals would mark a distinct change of course for a nation comprised entirely of former immigrants. But to address the non-resident population's needs through a dedicated housing supply or expedited naturalization, the country would assert itself as a nation of justice and opportunity, offering the highest quality of life for *all* who reside there.

9.2 Limitations of Modeling Approach and Results

The single greatest limitation to this study is the use of an aggregated, non-spatial modeling approach. The models described above are incapable of differentiating between distantly located units of housing or plots of land. As such, there is no accounting for varying physical or economic conditions on different parts of the island. One major improvement to this study would be to incorporate spatial data about existing housing and future allotted residential land into projections of housing prices and supply moving forward. Such a model would allow for consideration of effects such as increased land prices near the central business district, proximity of housing to public transportation and essential services, and the effects of land reclamation and future sea-level change scenarios on residential land availability.

Inherent in the shift toward disaggregated spatial modeling of residential land would be the need to reconsider the assumption that the pricing of housing can be modeled using a commodity method. Once housing is disaggregated spatially, the varying price of land based on location would necessitate modifications to the formulation of housing prices, especially in Singapore, where land cost can be a significant portion of the total value of a residential property. In order to extend the study in this manner, considerable existing geospatial data would need to be made available from a variety of government organizations, and the modeling methodology adapted accordingly.

As with all models, the Singapore Housing Market Model is an abstraction of a real system. Because of its simplicity, the model can only test certain policy approaches, and cannot reproduce or project point values exactly. The purpose of the model, rather, is to identify the important variables that effect the price and supply chain of housing in Singapore, understand their relationships to one another, and gain insight into the behavior patterns that different policy approaches generate.

The most pressing limitation of the model is in its calibration to historical data. Because housing price-demand elasticity data was not available, the model was calibrated by making assumptions and then fine-tuning the elasticity tables. Similarly, data for ‘soft’ variables—like the population’s mean desired occupant density—do not exist, so assumptions were made for these parameters and adjusted to calibrate the model.

Just as with the limitations in system comprehensiveness and data calibration, the results of the model are inherently limited. Results should be viewed as indications of trends, and expressions of fundamental behaviors produced by the structure of the model, and not used to predict specific past or future values.

Within these strict limitations, the model described in this study is a useful tool for distilling the complex housing market system into a readily understood set of relationships.

9.3 Further Application

In addition to its simplicity, the housing market model developed for this study seeks to be general. Starting from universal structures for commodity pricing and stock management, nothing in the proposed model should be unique to Singapore. While Singapore is a nearly ideal market for stock management, other less regulated markets could be simulated by relaxing some of the supply line accounting structures within the model, which is often done to simulate imperfect systems [64].

Similarly, by treating housing as an undifferentiated commodity, extension and calibration to other housing markets should be fairly straightforward. Limitations of time and resources prevented the adaptation to other markets from being included in this study, but this is certainly an area for future work.

Beyond direct adaptation of the existing model, there are several opportunities to apply the broader approach of this study to modeling the connection between socio-economic growth and physical resource demands in other urban contexts. Consider the following three examples for extending this work:

9.3.1 Understanding Price Bubbles

Over the last decade the housing markets in the United States have experienced a price bubble of unprecedented magnitude. It is widely accepted that the increased affordability during the late 1990s and early 2000s, through financial vehicles such as sub-prime mortgages, led to increased demand for housing and a speculative growth in price. When home prices peaked in 2006, rates of default and foreclosure on homes reached historic highs. The relative over-supply caused by excess building during the price run-up, and the subsequent flooding of repossessed homes onto the market is still being felt, six years later, as prices remain depressed.

While the price boom and bust was nearly ubiquitous throughout the country, the magnitude and aftereffects of the bubble are strikingly different from city-to-city. It is thought that local factors like land constraints, supply elasticity, development regulation, and financing policy account for the disparate range of regional outcomes.

The methodology proposed in this study, with very little modification, could be used to test the effects of varying elasticity of housing supply, residential density, land availability, and other supply-demand factors on the magnitude and resource implications of housing bubbles. This could lead to greater understanding and preparation for similar future events.

9.3.2 Planning and Zoning Regulations

The value of urban density is difficult to characterize because density is an aggregate measure of many variables. Glaeser cites increased innovation, economies of scale, and reduced resource consumption as inherent benefits to the density found in cities [2]. But density has not always been looked upon so favorably. From the smog-choked industrial cities of the late 19th century grew oppositions to urban development, like Ebenezer Howard's vision, the Garden City, which romanticized pastoral rural living for its open spaces and clean air. Many cities, especially those in former British colonies, like Mumbai, were planned on such low-density models. But today, with the world population exceeding 7 billion and concentrating rapidly in cities, the focus of development has returned to increasing density.

In order to support burgeoning urban populations, cities must evaluate and consider all of the parameters at their disposal to increase the supply of housing. And this means questioning historical precedent on issues of residential unit size, building height, plot ratio, etc. By assessing the long-term impacts of trends in a variety of density-influencing factors, a better projection of the future development patterns needed to provide for an exploding population within a city's given space constraints could be developed.

Because affordability is so closely linked with housing supply, by not providing adequate infrastructure and planning for housing, rapidly developing cities like Mumbai are forcing new arrivals to settle informally on the fringes of the city, leading to a whole host of additional problems.

9.3.3 Informal settlements

Throughout Africa, South America, and Asia, informal settlements—often referred to as "slums"—are the new centers of urban population growth. The promise of a better life in the city makes living in these squalid conditions favorable to remaining in perpetual agricultural poverty. As such, cities with limited infrastructure and inadequate housing supply are being inundated with newcomers from surrounding rural areas.

As these cities develop, the process of formalizing fringe settlements raises many fundamental questions: how to provide infrastructure to already established developments; how to redevelop single-story shacks into higher density, space-efficient housing; how to value land and determine ownership; how to finance new development.

By modeling existing formal markets in these cities, strategies for incorporating informal settlements into the city's overall housing supply could be evaluated and optimized. Similarly, monitoring and simulating population growth by considering rates of immigration could allow rapidly developing cities to plan and provide for anticipated future growth, formally.

9.4 Extension to Other Resource Intensity Measures

The most fruitful future work would be an extension of this model to simulate additional resource indicators, beyond residential land use. One in particular, construction material demand, could be generated directly from the already simulated floor area, through a material intensity factor. Considering material intensity would allow confirmation of the connection between housing bubbles—rapid price growth followed by rapid price decline—and resource inefficiency. This study goes only so far as to abstract material use from the per capita change in floor area. Actually determining the material resources required by large swings in price would strengthen the argument for policies that seek to moderate price oscillation.

This thesis extends several existing frameworks for carrying out dynamic material flow accounting and introduces the concept of land use flow accounting. It also utilizes seminal models of stock management and commodity dynamics to build insight into the relationship between housing supply, demand, and price. With the proposed additions and extensions, the models described above could contribute to a comprehensive approach to dynamically modeling and projecting resource flows, and assessing their effects on socio-economic processes. This feedback inherent in population-economy-resource systems is paramount in determining the behavior of the systems, and is a necessary consideration in the understanding of the urban metabolism.

Appendix A

Singapore Land Use Footprint Model (SLUFM) Diagram

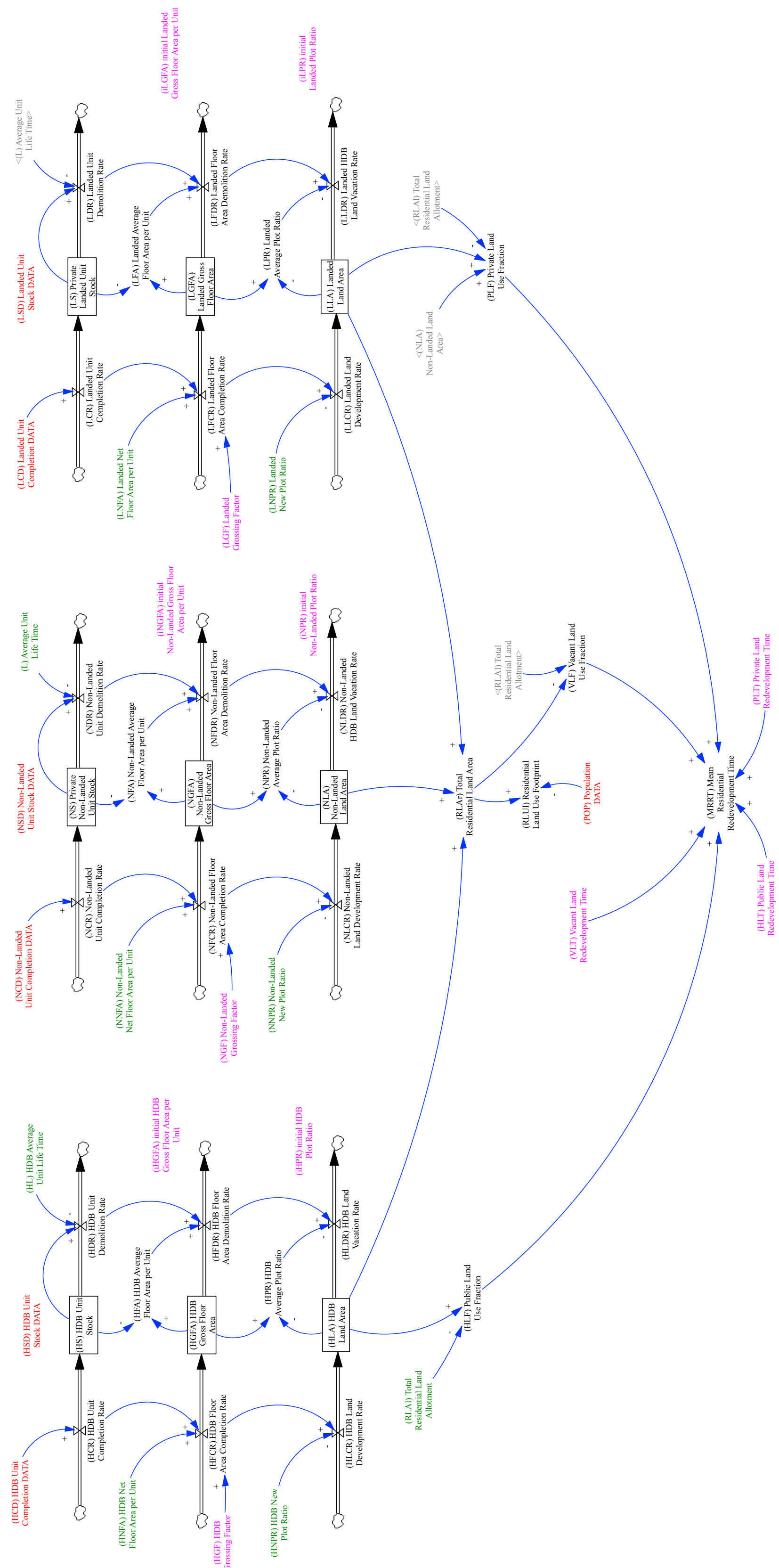

Figure A-1: Singapore land use footprint model: Part 1

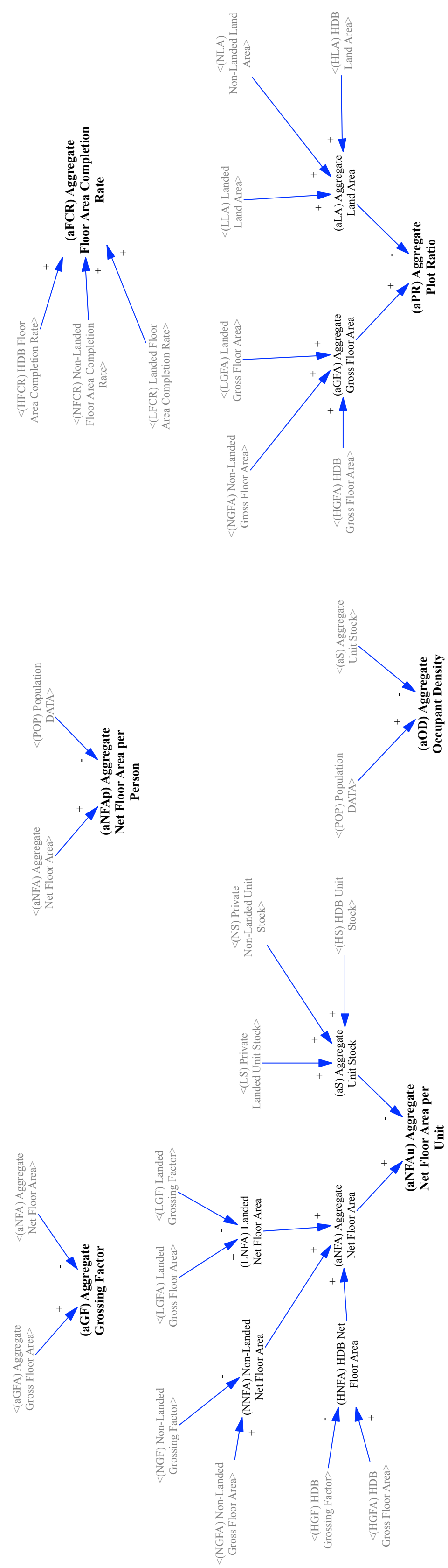

Figure A-2: Singapore land use footprint model: Part 2

Appendix B

Singapore Land Use Footprint Model (SLUFM) Documentation

(aFCR) Aggregate Floor Area Completion Rate, *sqm/Year*

$$aFCR = HFCR + LFCR + NFCR \quad \text{(B.1)}$$

Sum of public, private non-landed, and private landed floor area rate completion.

(aGF) Aggregate Grossing Factor, *Dmnl*

$$aGF = aGFA/aNFA \quad \text{(B.2)}$$

Total gross floor area divided by the total net floor area, gives the overall grossing factor for all housing.

(aGFA) Aggregate Gross Floor Area, *sqm*

$$aGFA = HGFA + LGFA + NGFA \quad \text{(B.3)}$$

Total gross floor area is the sum of the gross floor areas of public, private non-landed, and private non-landed housing.

(aLA) Aggregate Land Area, *sqm*

$$aLA = HLA + LLA + NLA \tag{B.4}$$

Total land area is the sum of the land areas of public, private non-landed, and private non-landed housing.

(aNFA) Aggregate Net Floor Area, *sqm*

$$aNFA = HNFA + LNFA + NNFA \tag{B.5}$$

Total net floor area is the sum of the net floor areas of public, private non-landed, and private non-landed housing.

(aNFAp) Aggregate Net Floor Area per Person, *sqm/Person*

$$aNFAp = aNFA/POP \tag{B.6}$$

Total net floor area divided by total population gives the per capita net floor area for all housing.

(aNFAu) Aggregate Net Floor Area per Unit, *sqm/Unit*

$$aNFAu = aNFA/aS \tag{B.7}$$

The total net floor area divided by the total unit stock gives the overall weighted mean net floor area per unit for all housing.

(aOD) Aggregate Occupant Density, *Person/Unit*

$$aOD = POP/aS \tag{B.8}$$

Total population divided by the total unit stock gives the mean occupant density for all housing.

(aPR) Aggregate Plot Ratio, *Dmnl*

$$aPR = aGFA/aLA \tag{B.9}$$

The total gross floor area divided by the total developed residential land area gives the overall weighted average plot ratio for all housing.

(aS) Aggregate Unit Stock, *Unit*

$$aS = HS + LS + NS \tag{B.10}$$

Total unit stock is the sum of the unit stocks of public, private non-landed, and private non-landed housing.

(HCD) HDB Unit Completion DATA, *Units/Year*

$$HCD = GETXLSDATA('SUM{-}MASTER{-}DATA.xls', 'LandUseData', 'A', 'C4') \tag{B.11}$$

Public Housing unit completion data, from HDB Annual Reports.

(HCR) HDB Unit Completion Rate, *Units/Year*

$$HCR = HCD \tag{B.12}$$

HDB Unit Completion Rate is fed directly from the reported data.

(HDR) HDB Unit Demolition Rate, *Units/Year*

$$HDR = HS/HL \tag{B.13}$$

HDB Unit Demolition Rate is calculated as the stock divided by the average lifetime of a unit, a simple first-order outflow.

(HFA) HDB Average Floor Area per Unit, *sqm/Unit*

$$HFA = HGFA/HS \tag{B.14}$$

HDB Average floor area per unit is the total floor area of all units in the stock, divided by the number of units in the stock.

(HFCR) HDB Floor Area Completion Rate, *sqm/Year*

$$HFCR = HCR * HNFA * HGF \tag{B.15}$$

Floor area completion rate is the product of unit completion rate, the current net floor area per unit and the grossing factor.

(HFDR) HDB Floor Area Demolition Rate, *sqm/Year*

$$HFDR = HDR * HFA \tag{B.16}$$

Floor area demolition rate is the product of unit demolition rate and the average floor area per unit of the current stock.

(HGF) HDB Grossing Factor, *Dmnl*

$$HGF = 1.6 \tag{B.17}$$

The factor that translates net floor area to gross floor area, accounts for wall thickness, circulation, building services, public spaces, and structured parking.

(HGFA) HDB Gross Floor Area, *sqm*

$$HGFA = INTEG(HFCR, HS * iHGFA) \tag{B.18}$$

HDB Gross Floor Area Stock is increased by new floor area completion and decreased by floor area demolition, and is initialized using the initial unit stock and initial gross floor area.

(HL) HDB Average Unit Life Time, *Year*

$$HL = 150 + STEP(350, 2000) \tag{B.19}$$

Average unit lifetime, controls outflow from stock of demolished units, calibrated so that the unit stock matches historical values.

(HLA) HDB Land Area, *sqm*

$$HLA = INTEG(HLCR, HGFA/iHPR) \tag{B.20}$$

Land Area Stock is increased by new land area development and decreased by land area vacation, and is initialized using the gross floor area stock and initial plot ratio.

(HLCR) HDB Land Development Rate, *sqm/Year*

$$HLCR = HFCR/HNPR \tag{B.21}$$

Floor area completion rate is the floor area completion rate divided by the current plot ratio.

(HLDR) HDB Land Vacation Rate, *sqm/Year*

$$HLDR = HFDR/HPR \tag{B.22}$$

Land area demolition rate is the floor area demolition rate divided by the average plot ratio of the current stock.

(HLF) Public Land Use Fraction, *Dmnl*

$$HLF = HLA/RLAl \tag{B.23}$$

The fraction of total land allotment made up by Public Housing.

(HLT) Public Land Redevelopment Time, *Year*

$$HLT = 10 \tag{B.24}$$

Assumed redevelopment time for public residential land, see Subsection 3.1.2.

(HNFA) HDB Net Floor Area per Unit, *sqm/Unit*

$$HNFA = 123 + RAMP(-2, 1990, 2011) \quad (B.25)$$

Average floor area of new public units by the Housing Development Board (HDB), measured in sqm/unit. This time-depended quantity is calculated from annual reports of unit completion, unit-type distribution, and unit-type floor area (as a function of time).

(HNFA) HDB Net Floor Area, *sqm*

$$HNFA = HGFA/HGF \quad (B.26)$$

Public net floor area is the gross floor area divided by the grossing factor.

(HNPR) HDB New Plot Ratio, *sqm/sqm*

$$HNPR = 2.8 + RAMP(0.01, 1990, 2011) \quad (B.27)$$

Based on data found in Leung2009, a trend was calculated for plot ratio of new HDB developements as a function of time. Generally, plot ratio of 2.8 was used for most of the HDB's history. In the last 20 years, more and more HDB developments are of than average higher-density. The trend to an average plot ratio of 3.0 is a current best-estimate.

(HPR) HDB Average Plot Ratio, *sqm/sqm*

$$HPR = HGFA/HLA \quad (B.28)$$

Average plot ratio is the total floor area of the stock divided by the total land area of the stock.

(HS) HDB Unit Stock, *Units*

$$HS = INTEG(HCR, HSD) \tag{B.29}$$

HDB Unit Stock is increased by new completions and decreased by demolitions. Since the inflow is controlled directly by a data stream, there is no first order control loop in this iteration of the model.

(HSD) HDB Unit Stock DATA, *Units*

$$HSD = GETXLSDATA('SUM\!-\!MASTER\!-\!DATA.xls','LandUseData','A','D4') \tag{B.30}$$

Public Housing unit stock, from HDB Annual Reports, for calibration of average lifetime.

(iHGFA) initial HDB Gross Floor Area per Unit, *sqm/Unit*

$$iHGFA = 137 \tag{B.31}$$

Sets the initial value for the HDB gross floor area stock.

(iHPR) initial HDB Plot Ratio, *Dmnl*

$$iHPR = 2.8 \tag{B.32}$$

Sets the initial value for the HDB land area stock.

(iLGFA) initial Landed Gross Floor Area per Unit, *sqm/Unit*

$$iLGFA = 380 \tag{B.33}$$

Sets the initial value for the landed gross floor area stock.

(iLPR) initial Landed Plot Ratio, *Dmnl*

$$iLPR = 1.1 \tag{B.34}$$

Sets the initial value for the Non-Landed land area stock.

(iNGFA) initial Non-Landed Gross Floor Area per Unit, *sqm/Unit*

$$iNGFA = 177 \tag{B.35}$$

Sets the initial value for the non-landed gross floor area stock.

(iNPR) initial Non-Landed Plot Ratio, *Dmnl*

$$iNPR = 2.3 \tag{B.36}$$

Sets the initial value for the Non-Landed land area stock.

(L) Average Unit Life Time, *Year*

$$L = 150 \tag{B.37}$$

Average service life of a typical housing unit. The value used is almost certainly too high, however given the young age of most of the residential building stock in Singapore, the actual demolition rate is currently much lower than it will likely be when it reaches equilibrium. This value was obtained, empirically, by using the actual (ORD) Unit Initiation Rate DATA for (OR) Unit Initiation Rate, and adjusting the (L) Average Unit Life Time until the modeled stock (S) matched the (SD) Unit Stock DATA.

(LCD) Landed Unit Completion DATA, *Units/Year*

$$LCD = GETXLSDATA('SUM\text{-}MASTER\text{-}DATA.xls', 'LandUseData', 'A', 'I4') \tag{B.38}$$

(LCR) Landed Unit Completion Rate, *Units/Year*

$$LCR = LCD \tag{B.39}$$

Landed Unit Completion Rate is fed directly from the reported data.

(LDR) Landed Unit Demolition Rate, *Units/Year*

$$LDR = LS/L \tag{B.40}$$

Landed Unit Demolition Rate is calculated as the stock divided by the average lifetime of a unit, a simple first-order outflow.

(LFA) Landed Average Floor Area per Unit, *sqm/Unit*

$$LFA = LGFA/LS \tag{B.41}$$

Landed Average floor area per unit is the total floor area of all units in the stock, divided by the number of units in the stock.

(LFCR) Landed Floor Area Completion Rate, *sqm/Year*

$$LFCR = LCR * LNFA * LGF \tag{B.42}$$

Floor area completion rate is the product of unit completion rate, the current net floor area per unit and the grossing factor.

(LFDR) Landed Floor Area Demolition Rate, *sqm/Year*

$$LFDR = LDR * LFA \tag{B.43}$$

Floor area demolition rate is the product of unit demolition rate and the average floor area per unit of the current stock.

(LGF) Landed Grossing Factor, *Dmnl*

$$LGF = 1.3 \tag{B.44}$$

The factor that translates net floor area to gross floor area, accounts for wall thickness, circulation, building services, public spaces, and structured parking.

(LGFA) Landed Gross Floor Area, *sqm*

$$LGFA = INTEG(LFCR, LS * iLGFA) \tag{B.45}$$

Landed Gross Floor Area Stock is increased by new floor area completion and decreased by floor area demolition, and is initialized using the initial unit stock and initial gross floor area.

(LLA) Landed Land Area, *sqm*

$$LLA = INTEG(LLCR, LGFA/iLPR) \tag{B.46}$$

Land Area Stock is increased by new land area development and decreased by land area vacation, and is initialized using the gross floor area stock and initial plot ratio.

(LLCR) Landed Land Development Rate, *sqm/Year*

$$LLCR = LFCR/LNPR \tag{B.47}$$

Floor area completion rate is the floor area completion rate divided by the current plot ratio.

(LLDR) Landed HDB Land Vacation Rate, *sqm/Year*

$$LLDR = LFDR/LPR \tag{B.48}$$

Land area demolition rate is the floor area demolition rate divided by the average plot ratio of the current stock.

(LNFA) Landed Net Floor Area per Unit, *sqm/Unit*

$$LNFA = 276 \tag{B.49}$$

Average floor area of new private landed units, measured in sqm/unit. This quantity is calculated from land and unit sales data, compiled by the URA.

(LNFA) Landed Net Floor Area, *sqm*

$$LNFA = LGFA/LGF \tag{B.50}$$

Private landed net floor area is the gross floor area divided by the grossing factor.

(LNPR) Landed New Plot Ratio, *sqm/sqm*

$$LNPR = 1.2 \tag{B.51}$$

Landed housing plot ratios have stayed fairly constant over the last two decades. The weighted average was calculated from land and unit sales data.

(LPR) Landed Average Plot Ratio, *sqm/sqm*

$$LPR = LGFA/LLA \tag{B.52}$$

Average plot ratio is the total floor area of the stock divided by the total land area of the stock.

(LS) Private Landed Unit Stock, *Units*

$$LS = INTEG(LCR, LSD) \tag{B.53}$$

Landed Unit Stock is increased by new completions and decreased by demolitions. Since the inflow is controlled directly by a data stream, there is no first order control loop in this iteration of the model.

(LSD) Landed Unit Stock DATA, *Units*

$$LSD = GETXLSDATA('SUM-MASTER-DATA.xls', 'LandUseData', 'A', 'J4') \tag{B.54}$$

Landed Private Housing unit stock, from Yearbook of Statistics.

(MRRT) Mean Residential Redevelopment Time, *Year*

$$MRRT = (VLF * VLT) + (HLF * HLT) + (PLF * PLT) \tag{B.55}$$

The weighted average of redevelopment times by land use fraction for each of the three residential land use types modeled: public, private, and vacant, see Subsection 3.1.2.

(NCD) Non-Landed Unit Completion DATA, *Units/Year*

$$NCD = GETXLSDATA('SUM{-}MASTER{-}DATA.xls', 'LandUseData', 'A', 'F4') \tag{B.56}$$

(NCR) Non-Landed Unit Completion Rate, *Units/Year*

$$NCR = NCD \tag{B.57}$$

Non-Landed Unit Completion Rate is fed directly from the reported data.

(NDR) Non-Landed Unit Demolition Rate, *Units/Year*

$$NDR = NS/L \tag{B.58}$$

Non-Landed Unit Demolition Rate is calculated as the stock divided by the average lifetime of a unit, a simple first-order outflow.

(NFA) Non-Landed Average Floor Area per Unit, *sqm/Unit*

$$NFA = NGFA/NS \tag{B.59}$$

Non-Landed Average floor area per unit is the total floor area of all units in the stock, divided by the number of units in the stock.

(NFCR) Non-Landed Floor Area Completion Rate, *sqm/Year*

$$NFCR = NCR * NNFA * NGF \tag{B.60}$$

Floor area completion rate is the product of unit completion rate, the current net floor area per unit and the grossing factor.

(NFDR) Non-Landed Floor Area Demolition Rate, *sqm/Year*

$$NFDR = NDR * NFA \tag{B.61}$$

Floor area demolition rate is the product of unit demolition rate and the average floor area per unit of the current stock.

(NGF) Non-Landed Grossing Factor, *Dmnl*

$$NGF = 1.7 \tag{B.62}$$

The factor that translates net floor area to gross floor area, accounts for wall thickness, circulation, building services, public spaces, and structured parking.

(NGFA) Non-Landed Gross Floor Area, *sqm*

$$NGFA = INTEG(NFCR, NS * iNGFA) \tag{B.63}$$

Non-Landed Gross Floor Area Stock is increased by new floor area completion and decreased by floor area demolition, and is initialized using the initial unit stock and initial gross floor area.

(NLA) Non-Landed Land Area, *sqm*

$$NLA = INTEG(NLCR, NGFA/iNPR) \tag{B.64}$$

Land Area Stock is increased by new land area development and decreased by land area vacation, and is initialized using the gross floor area stock and initial plot ratio.

(NLCR) Non-Landed Land Development Rate, *sqm/Year*

$$NLCR = NFCR/NNPR \tag{B.65}$$

Floor area completion rate is the floor area completion rate divided by the current plot ratio.

(NLDR) Non-Landed HDB Land Vacation Rate, *sqm/Year*

$$NLDR = NFDR/NPR \tag{B.66}$$

Land area demolition rate is the floor area demolition rate divided by the average plot ratio of the current stock.

(NNFA) Non-Landed Net Floor Area per Unit, *sqm/Unit*

$$NNFA = 119 \tag{B.67}$$

Average floor area of new private non-landed units, measured in sqm/unit. This quantity is calculated from land and unit sales data, compiled by the URA.

(NNFA) Non-Landed Net Floor Area, *sqm*

$$NNFA = NGFA/NGF \tag{B.68}$$

Private non-landed net floor area is the gross floor area divided by the grossing factor.

(NNPR) Non-Landed New Plot Ratio, *sqm/sqm*

$$NNPR = 2.2 + RAMP(0.05, 1990, 2011) \tag{B.69}$$

Regressed from unit and land sales data, the plot ratio of non-landed private units has increased significantly over the last 20 years.

(NPR) Non-Landed Average Plot Ratio, *sqm/sqm*

$$NPR = NGFA/NLA \tag{B.70}$$

Average plot ratio is the total floor area of the stock divided by the total land area of the stock.

(NS) Private Non-Landed Unit Stock, *Units*

$$NS = INTEG(NCR, NSD) \tag{B.71}$$

Non-Landed Unit Stock is increased by new completions and decreased by demolitions. Since the inflow is controlled directly by a data stream, there is no first order control loop in this iteration of the model.

(NSD) Non-Landed Unit Stock DATA, *Units*

$$NSD = GETXLSDATA('SUM{-}MASTER{-}DATA.xls', 'LandUseData', 'A', 'G4') \tag{B.72}$$

Non-Landed Private Housing unit stock, from Yearbook of Statistics, for calibration of average lifetime.

(PLF) Private Land Use Fraction, *Dmnl*

$$PLF = (\text{"}(NLA)Non - LandedLandArea\text{"} + LLA)/RLAl \tag{B.73}$$

The fraction of total land allotment made up by Private Housing.

(PLT) Private Land Redevelopment Time, *Year*

$$PLT = 20 \tag{B.74}$$

Assumed redevelopment time for private residential land, see Subsection 3.1.2.

(POP) Population DATA, *Person*

$$POP = GETXLSDATA('SUM{-}MASTER{-}DATA.xls', 'QuarterlyData', 'A', 'Y3') \tag{B.75}$$

Total population of Singapore, data from SingSTAT Annual statistics.

(RLAl) Total Residential Land Allotment, *sqm*

$$RLAl = 1.289e + 08 \tag{B.76}$$

Total area of all land zoned for residential use, present and future.

(RLAr) Total Residential Land Area, *sqm*

$$RLAr = HLA + NLA + LLA \tag{B.77}$$

Total residentially developed land area, the sum of the three types of modeled housing land area: public, private non-landed, and private landed.

(RLUI) Residential Land Use Footprint, *sqm/Person*

$$RLUI = RLAr/POP \tag{B.78}$$

The per-capita residential land area, calculated as the total developed residential land area divided by the total population.

(VLF) Vacant Land Use Fraction, *Dmnl*

$$VLF = ("(RLAl)TotalResidentialLandAllotment" - RLAr)/RLAl \tag{B.79}$$

The fraction of total land allotment as yet undeveloped.

(VLT) Vacant Land Redevelopment Time, *Year*

$$VLT = 5 \tag{B.80}$$

Assumed redevelopment time for vacant residential land, see Subsection 3.1.2.

(FINALTIME), *Year*

$$FINALTIME = 2011 \tag{B.81}$$

The final time for the simulation.

(INITIALTIME), *Year*

$$INITIALTIME = 1990 \tag{B.82}$$

The initial time for the simulation.

(SAVEPER), *Year[0,?]*

$$SAVEPER = 0.25 \tag{B.83}$$

The frequency with which output is stored.

(TIMESTEP), *Year[0,?]*

$$TIMESTEP = 0.0625 \tag{B.84}$$

The time step for the simulation.

Appendix C

Singapore Housing Market Model (SHMM) Diagram

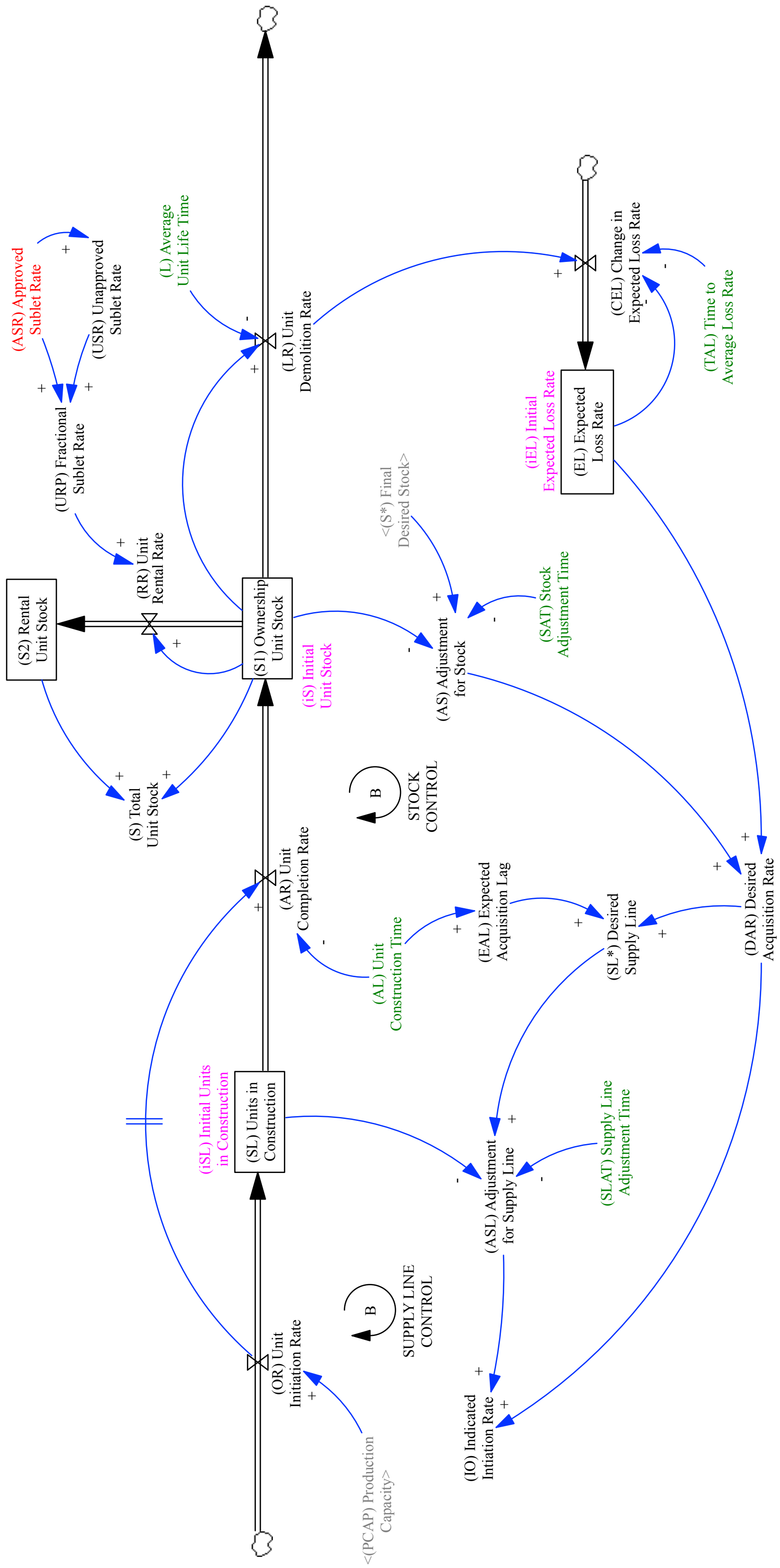

Figure C-1: Singapore housing market model: Part A

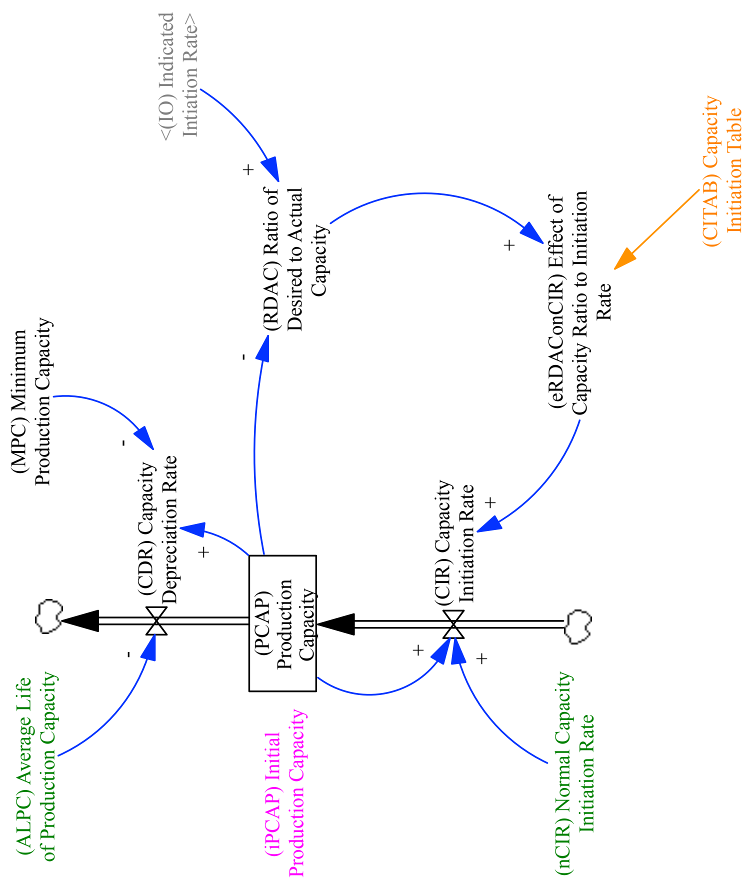

Figure C-2: Singapore housing market model: Part B

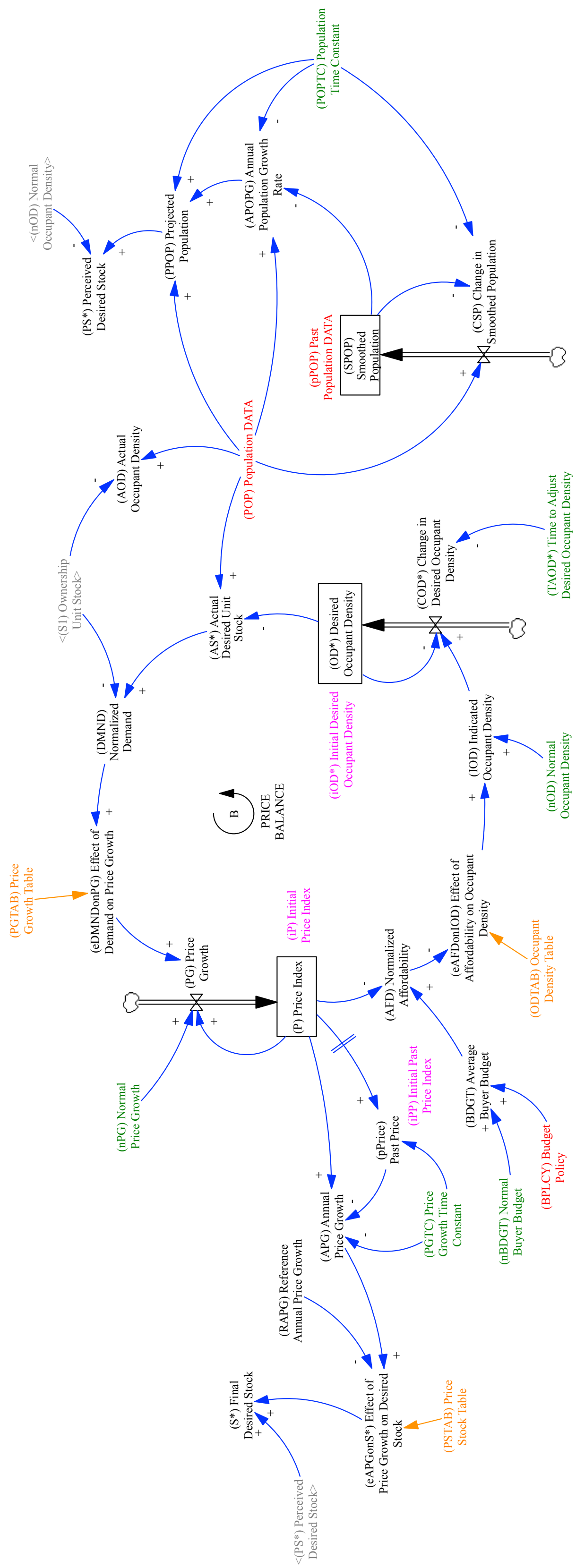

Figure C-3: Singapore housing market model: Part C

Appendix D

Singapore Housing Market Model (SHHM) Documentation

(AFD) Normalized Affordability, *Dmnl*

$$AFD = BDGT/P \tag{D.1}$$

Normalized affordability is the ratio of Buyer Budget to Price. When budget exceeds price, affordability is greater than 1, and the converse is true.

(AL) Unit Construction Time, *Year*

$$AL = 3 \tag{D.2}$$

Average time to construct a unit of housing. The HDB (public) plans for 2.5 years, and the URA (private) assumes 4 years. Given the larger share of public housing, a value closer to that end was chosen.

(ALPC) Average Life of Production Capacity, *Year*

$$ALPC = 2 \tag{D.3}$$

Most Singaporean construction laborers are migrant workers who have short term work permits, 2 years, which must be renewed to keep them working. This allows for a very fast contraction of the construction industry in times when few new housing are needed.

(AOD) Actual Occupant Density, *Person/Unit*

$$AOD = POP/S1 \tag{D.4}$$

The Actual occupant density is the current population (POP) divided by the current total ownership stock (S1).

(APG) Annual Price Growth, *1/Year*

$$APG = (P - pPrice)/pPrice/PGTC \tag{D.5}$$

Annual price growth in percent per year is calculated by comparing the percentage difference of the current price and the past price, and dividing by the time difference between samplings, in this case 0.5 years.

(APOPG) Annual Population Growth Rate, *1/Year*

$$APOPG = ((POP - SPOP)/SPOP)/POPTC \tag{D.6}$$

The annual population growth rate is calculated by finding the total percentage growth in population between the current and past signals, and then dividing by the time constant.

(AR) Unit Completion Rate, *Units/Year*

$$AR = DELAY3(OR, AL) \tag{D.7}$$

Rate at which units in construction are completed. Governed by a third order delay of the input to the stock, (OR) Unit Initiation Rate, delayed by the (AL) Unit Construction Time.

(AS) Adjustment for Stock, *Unit/Year*

$$AS = (S * -S1)/SAT \tag{D.8}$$

The adjustment for stock is the difference between the actual (S) and desired stock (S*). Because the adjustment is made over several years, that difference is divided by the (SAT) Stock Adjustment Time, giving an adjustment rate in units/year.

(AS*) Actual Desired Unit Stock, *Units*

$$AS* = POP/OD* \tag{D.9}$$

The Actual Desired Unit Stock is the number of units 'demanded' by the current population. It is calculated as the current Population (POP) divided by the current Desired Occupant Density (OD*).

(ASL) Adjustment for Supply Line, *Unit/Year*

$$ASL = (SL * -SL)/SLAT \tag{D.10}$$

Like (AS) Adjustment for Stock, (ASL) Adjustment for Supply Line compares the (SL*) Desired Supply Line to the actual (SL) Units in Construction. This difference is divided by the (SLAT) Supply Line Adjustment Time.

(ASR) Approved Sublet Rate, *1/Year*

$$ASR = 0 + STEP(0.015, 2007) + STEP(0.01, 2008) \tag{D.11}$$

Based on a suite of policies initiated in 2007 and continued through 2010, a percentage of public units were approved to be sublet to non-residents, therefor removing them from the stock of units available for purchase by citizens and permanent residents. Actual rates based on data from the HDB on Sublet Approvals.

(BDGT) Average Buyer Budget, *Dollars/Unit*

$$BDGT = nBDGT * BPLCY \tag{D.12}$$

Actual Buyer Budget is the normal buyer budget multiplied by the effect of policies on buyer budget.

(BPLCY) Budget Policy, *Dmnl*

$$BPLCY = 1 + STEP(1.22, 1993) \tag{D.13}$$

The only change in budget comes from the policies enacted between 1993 and 1996 regarding housing affordability. For simplicity, these policies have been combined into a single budget increase of about 122% in 1993.

(CDR) Capacity Depreciation Rate, *Units/Year/Year*

$$CDR = IFTHENELSE(PCAP > MPC, PCAP/ALPC, 0) \tag{D.14}$$

Capacity depreciation is the result of work permits expiring, limited by a minimum government maintained (PCAP) Production Capacity.

(CEL) Change in Expected Loss Rate, *Units/(Year*Year)*

$$CEL = (LR - EL)/TAL \tag{D.15}$$

Change in expected loss rate is calculated by dividing the difference between (LR) and (EL) by (TAL). This flow performs the first order signal smoothing operation.

(CIR) Capacity Initiation Rate, *Units/Year/Year*

$$CIR = PCAP * nCIR * eRDAConCIR \tag{D.16}$$

Capacity Initiation is the product of the current (PCAP) Production Capacity and the Capacity Initiation Rate, which is the (nCIR) Normal Capacity Initiation Rate modified by the effect of (RDAC) Ratio of Desired to Actual Capacity.

(CITAB) Capacity Initiation Table, *Dmnl*

$$CITAB = [(-12, 0) - (12, 2)], (-12, 0.5), (-2, 0.5), (-1, 0.55), (0, 0.65), (0.5, 0.75), (1, 1), (1.5, 1.4), (2, 1.55), (12, 1.55)) \tag{D.17}$$

Table Function relating the (RDAC) Ratio of Desired to Actual Capacity to its effect on (CIR) Capacity Initiation Rate.

(COD*) Change in Desired Occupant Density, *Person/(Unit*Year)*

$$COD* = (IOD - OD*)/TAOD* \tag{D.18}$$

The flow that smoothes the desired occupant density follows the standard equation of comparing the current Desired Occupant Density with the Indicated Occupant Density, and dividing the difference by the Adjustment Time.

(CSP) Change in Smoothed Population, *Person/Year*

$$CSP = (POP - SPOP)/POPTC \tag{D.19}$$

The flow that smoothes the population follows the standard equation of comparing the current population with the past population, and dividing the difference by the smoothing time constant. The output signal (SPOP) is a 3-year smoothed and shifted version of the input signal (POP).

(DAR) Desired Acquisition Rate, *Unit/Year*

$$DAR = MAX(0, EL + AS) \tag{D.20}$$

Desired Acquisition Rate is the sum of the (EL) Expected Loss Rate and (AS) Adjustment for Stock. This term makes up the core of the "Stock Control" balancing loop, which assures that sufficient units will be initiated to replace losses and reach the desired stock.

(DMND) Normalized Demand, *Dmnl*

$$DMND = AS * /S1 \tag{D.21}$$

Normalized Demand is the ratio of Desired Unit Stock (AS*) to the current available Stock (S1).

(eAFDonIOD) Effect of Affordability on Occupant Density, *Dmnl*

$$eAFDonIOD = ODTAB(AFD) \tag{D.22}$$

The Effect on (IOD) Indicated Occupant Density as a function of (AFD) Normalized Affordability.

(EAL) Expected Acquisition Lag, *Year*

$$EAL = AL \tag{D.23}$$

In this model, the (AL) Unit Construction Time never varies, so (EAL) Expected Acquisition Lag is equal to the (AL) Unit Construction Time.

(eAPGonS*) Effect of Price Growth on Desired Stock, *Dmnl*

$$eAPGonS* = PSTAB(APG/RAPG) \tag{D.24}$$

The Effect on (S*) Final Desired Stock as a function of normalized (APG) Annual Price Growth.

(eDMNDonPG) Effect of Demand on Price Growth, *Dmnl*

$$eDMNDonPG = PGTAB(DMND) \tag{D.25}$$

The Effect on (PG) Price Growth as a function of (DMND) Normalized Demand.

(EL) Expected Loss Rate, *Units/Year*

$$EL = INTEG(CEL, iEL) \tag{D.26}$$

The expected number of units to be demolished in a given year. It is a smoothed version of the actual (LR) Unit Demolition Rate.

(eRDAConCIR) Effect of Capacity Ratio to Initiation Rate, *Dmnl*

$$eRDAConCIR = CITAB(RDAC) \tag{D.27}$$

The Effect on (CIR) Capacity Initiation Rate as a function of (RDAC) Ratio of Desired to Actual Capacity.

(iEL) Initial Expected Loss Rate, *Units/Year*

$$iEL = 4847 \tag{D.28}$$

(iEL) Initial Expected Loss Rate is calculated by dividing the (iS) Initial Unit Stock by the (L) Average Unit Life Time.

(IO) Indicated Intiation Rate, *Units/Year*

$$IO = DAR + ASL \tag{D.29}$$

Indicated Initation is the desired number of units to be initiated in a given year. In an ideal situation this number of units would actually be initiated each year, however, in a real system the number of initiations is bound (both upper and lower) by the capacity of the residential building construction industry.

(IOD) Indicated Occupant Density, *Person/Unit*

$$IOD = nOD * eAFDonIOD \tag{D.30}$$

Indicated occupant density is the normal occupant density shifted up or down by the effect of current affordability. When affordability is less than one, occupants only recourse is to live more people to a unit (grown children do not move to new units, elderly grandparents remain living with their children, families share housing units, etc.) in order to afford the more expensive housing.

(iOD*) Initial Desired Occupant Density, *Person/Units*

$$iOD* = 4.1 \tag{D.31}$$

Initial desired occupant density is set equal to the normal occupant density, 4.1.

(iP) Initial Price Index, *Dollars/Unit*

$$iP = 45 \tag{D.32}$$

The initial price index value is taken directly from the weighted-average, deflated price index data.

(iPCAP) Initial Production Capacity, *Units/Year*

$$iPCAP = 19168 \tag{D.33}$$

Initial production capacity is equal to the initial (OR) Unit Initiation Rate. Taken directly from HDB and YOS data.

(iPP) Initial Past Price Index, *Dollars/Unit*

$$iPP = 43.2 \tag{D.34}$$

The initial past price index is taken from the price index data, which is available for several time periods before the simulation begins.

(iS) Initial Unit Stock, *Units*

$$iS = 727010 \tag{D.35}$$

Initial housing unit stock. Taken directly from (SD) Unit Stock DATA.

(iSL) Initial Units in Construction, *Units*

$$iSL = 36382 \tag{D.36}$$

Initial housing units in construction stock. Taken directly from HDB and YOS data.

(L) Average Unit Life Time, *Year*

$$L = 150 \tag{D.37}$$

Average service life of a typical housing unit. The value used is almost certainly too high, however given the young age of most of the residential building stock in Singapore, the actual demolition rate is currently much lower than it will likely be when it reaches equilibrium. This value was obtained, empirically, by using the actual (ORD) Unit Initiation Rate DATA for (OR) Unit Initiation Rate, and adjusting the (L) Average Unit Life Time until the modeled stock (S) matched the (SD) Unit Stock DATA.

(LR) Unit Demolition Rate, *Units/Year*

$$LR = S1/L \tag{D.38}$$

The rate at which units are demolished. Governed by the first order material delay, (S) Stock / (L) Average Residence Time.

(MPC) Minimum Production Capacity, *Units/Year*

$$MPC = 10000 \tag{D.39}$$

Based on (ORD) Unit Initiation Rate DATA, it can be seen that despite a stagnant market and more-than-sufficient supply, a minimum of 10,000 new residential units were initiated each year. For this reason, a minimum limit to the (PCAP) stock of 10,000 units/year is implemented through this term.

(nBDGT) Normal Buyer Budget, *Dollars/Unit*

$$nBDGT = 45 \tag{D.40}$$

Average buyer budget is a complex term that would take into account many variables about a household's ability and willingness to pay for housing. However, in this simplified model, we assume that buyer budget is essentially proportional to the CPI, and since all monetary values are depreciated by the CPI, average buyer budget remains constant throughout the simulation.

(nCIR) Normal Capacity Initiation Rate, *1/Year*

$$nCIR = 0.5 \tag{D.41}$$

Normal Capacity Initiation Rate, 50% per year, is set to balance the rate at which production capacity depreciates (also by 50% per year), when the system is in equilibrium.

(nOD) Normal Occupant Density, *Person/Units*

$$nOD = 4.1 \tag{D.42}$$

For this model, a constant value of 4.1 people per unit is used as the 'normal' occupant density. This value was chosen because the actual occupant density oscillates around a baseline of about 4.1 people per unit during the time period 1990-2011.

(nPG) Normal Price Growth, *1/Year*

$$nPG = 0.25 \tag{D.43}$$

Baseline price growth rate in % per year. This number is paired with the slope and minimum/maximum of table function (PGTAB). At equilibrium (PG) Price Growth is 0% per year.

(OD*) Desired Occupant Density, *Person/Units*

$$OD* = INTEG(COD*, iOD*) \tag{D.44}$$

Desired occupant density is a smoothed version of the indicated occupant density. This smoothing occurs becuase occupants beliefs about how densly to live takes some time to adjust.

(ODTAB) Occupant Density Table, *Dmnl*

$$ODTAB = [(0,0)-(4,2)],(0,1.5),(0.5,1.5),(0.75,1.25),(0.9,1.1),(1,1),$$
$$(1.1,0.8),(1.25,0.5),(2,0.5),(4,0.5)) \tag{D.45}$$

Table Function relating (AFD) Normalized Affordability to its effect on (IOD) Indicated Occupant Density.

(OR) Unit Initiation Rate, *Units/Year*

$$OR = PCAP \tag{D.46}$$

The number of new units initiated each year. It is assumed that this number is equal to the current (PCAP) Production Capacity. This structure is consistent with both Supply Chain Management and Commodity Cycle models.

(ORD) Unit Initiation Rate DATA, *Units/Year*

$$ORD = GETXLSDATA('SUM\text{-}MASTER\text{-}DATA.xls', 'QuarterlyData', 'A', 'S3') \tag{D.47}$$

Unit Initiation Rate is the number of new unit initiations (construction starts) each year. Public unit data is from the HDB Annual Reports, and Private data is reported in the Yearbook of Statistics.

(P) Price Index, *Dollars/Unit*

$$P = INTEG(PG, iP) \tag{D.48}$$

Price Index is an indicator of relative price of housing over time. It is derived from surveys of actual home sales and market conditions, and is an aggregate value for all types of housing. For this model, private and public price indexes have been aggregated by a weighted average of 80% public and 20% private (roughly the market share of each). The reference price index is also deflated by the CPI, normalized to 100 at 1998Q4.

(PCAP) Production Capacity, *Units/Year*

$$PCAP = INTEG(CIR, iPCAP) \tag{D.49}$$

A measure of the size of the residential construction industry, measured in production capacity (units/year). This capacity is equal to the (OR) Unit Initiation Rate, so adjustments in (OR) Unit Initiation Rate occur through expansion and contraction of (PCAP) Production Capacity.

(PD) Price Index DATA, *Dollars/Unit*

$$PD = GETXLSDATA('SUM\text{-}MASTER\text{-}DATA.xls', 'QuarterlyData', 'A', 'F3') \tag{D.50}$$

Quarterly Data of Residential Price Index in Singapore from 1990-2011. Price Index is a weighted average of the Public Resale and Private Market Price Indexes (80% and 20% respectively). Price Index is also inflation adjusted by the Consumer Price Index (CPI) and normalized to 1998, Quarter 4 = 100. Source: Monthly Digest of Statistics.

(PG) Price Growth, *Dollars/Unit/Year*

$$PG = P * nPG * eDMNDonPG \tag{D.51}$$

Actual price growth is the product of current price (P), normal price growth rate (nPG), and the effect of demand on price growth (eDMNDonPG). Since this is a non-material flow it can take both positive and negative values.

(PGTAB) Price Growth Table, *Dmnl*

$$PGTAB = [(0, -2) - (2, 2)], (0, -2), (0.5, -2), (0.7, -1.8), (0.85, -1.2),$$
$$(0.95, -0.6), (1, 0), (1.1, 0.6), (1.25, 1.2), (1.5, 1.8), (1.75, 2), (2, 2)) \quad (D.52)$$

Table Function relating (DMND) Normalized Demand to its effect on (PG) Price Growth.

(PGTC) Price Growth Time Constant, *Year*

$$PGTC = 0.5 \quad (D.53)$$

Price growth time constant is the frequency with which price growth is calculated. Smaller values here result in greater fluctuation in Annual Price Growth (APG). While price growth is calculated quarterly, the assumption is that decisions about price are made with a slightly longer view, of 2 quarters.

(POP) Population DATA, *Person*

$$POP = GETXLSDATA('SUM{-}MASTER{-}DATA.xls', 'QuarterlyData', 'A', 'Y3') \quad (D.54)$$

Population Data is the total aggregate population (citizen + permanent resident + non-resident) of Singapore, as reported by the SingSTAT Time Series on Population.

(POPTC) Population Time Constant, *Year*

$$POPTC = 3 \quad (D.55)$$

Because the construction time is known to be about 3 years, the projected population is made for 3 years in the future by this time constant.

(pPOP) Past Population DATA, *Person*

$$pPOP = GETXLSDATA('SUM - MASTER - DATA.xls', 'PastData', 'A', 'D3') \tag{D.56}$$

The initial past population is taken from the data, which goes back further than the time scope of the model.

(PPOP) Projected Population, *Person*

$$PPOP = POP * EXP(APOPG * POPTC) \tag{D.57}$$

Projected Population is the population expected X years in the future, where X is equal to the Population Time Constant. It is calculated using the exponential growth equation, A2 = A1*EXP(RATE*TIME).

(pPrice) Past Price, *Dollars/Unit*

$$pPrice = DELAYFIXED(P, PGTC, iPP) \tag{D.58}$$

This is the past price, taken at the current time minus the price growth time constant. The initial value is set by the (iPP).

(PS*) Perceived Desired Stock, *Unit*

$$PS* = PPOP/nOD \tag{D.59}$$

Perceived Desired Stock is the Projected Population (PPOP) divided by the Normal Occupant Density (nOD).

(PSTAB) Price Stock Table, *Dmnl*

$$PSTAB = [(-1,0)-(1,2)],(-1,0.9),(-0.4,0.9),(-0.2,0.91),(0,1),(0.5,1.05),(1,1.05)) \quad (D.60)$$

Table Function relating normalized (APG) Annual Price Growth to its effect on (S*) Final Desired Stock.

(RAPG) Reference Annual Price Growth, *1/Year*

$$RAPG = 1 \quad (D.61)$$

Reference growth is used to normalize the Annual Price Growth (APG) to a dimensionless quantity, so that it can be put into the (PSTAB) table function.

(RDAC) Ratio of Desired to Actual Capacity, *Dmnl*

$$RDAC = IO/PCAP \quad (D.62)$$

The ratio of the actual intiation rate (Production Capacity) and the desired intiation rate (Indicated Initiation Rate). A ratio ¿ 1 initiates production capacity growth, while a ratio ¡ 1 initiates capacity contraction.

(RR) Unit Rental Rate, *Units/Year*

$$RR = S1 * URP \quad (D.63)$$

The rate (units/year) at which ownership units are transferred to whole-unit non-resident sublets.

(S) Total Unit Stock, *Unit*

$$S = S1 + S2 \tag{D.64}$$

Total stock is the sum of ownership and rental units. It is used to compare to the (SD) actual Unit Stock DATA.

(S*) Final Desired Stock, *Unit*

$$S* = PS * *eAPGonS* \tag{D.65}$$

Final Desired Stock (S*) is the Perceived Desired Stock (PS*), adjusted up or down by the effect of Price Growth (eAPGonS*). It is the projected total number of units that will be needed 3 years from today.

(S1) Ownership Unit Stock, *Units*

$$S1 = INTEG(AR, iS) \tag{D.66}$$

Stock of ownership (not whole unit sublet to non-residents) public and private completed units in service.

(S2) Rental Unit Stock, *Units*

$$S2 = INTEG(RR, 0) \tag{D.67}$$

Stock of units being sublet to non-residents, and therefor not fully accounted for in housing supply calculations. This stock has an initial value of zero, and only begins to fill after the policies of 2007 are implemented.

(SAT) Stock Adjustment Time, *Year*

$$SAT = 5 \tag{D.68}$$

The average time to adjust the stock from its current state (S) to the new desired state (S*). In Singapore the HDB (Public Housing Authority) plans and builds units on a 5 year cycle, so we assume the average time to adjust the building supply to be 5 years.

(SD) Unit Stock DATA, *Units*

$$SD = GETXLSDATA('SUM-MASTER-DATA.xls', 'QuarterlyData', 'A', 'V3') \tag{D.69}$$

Unit Stock Data is the sum of all public and private residential units in service. Public unit counts are from the HDB Annual Reports, and Private stock is reported in the Yearbook of Statistics.

(SL) Units in Construction, *Units*

$$SL = INTEG(OR, iSL) \tag{D.70}$$

Housing units in construction. Units are delayed here between being initiated and completed.

(SL*) Desired Supply Line, *Unit*

$$SL* = EAL * DAR \tag{D.71}$$

Desired supply line is the number of units needed ‘in progress’ to assure that the (DAR) Desired Acquisition Rate can be met. It is calculated by multiplying the annual acquisition rate (DAR) by the number of years units spend in the supply line (EAL).

(SLAT) Supply Line Adjustment Time, *Year*

$$SLAT = 1 \tag{D.72}$$

Both the HDB (Public Housing Authority) and URA (Private Housing Authority) update housing calculations on an annual basis to ensure that their 5 year building goals can be met. So the (SLAT) Supply Line Adjustment Time is set to 1 year.

(SPOP) Smoothed Population, *Person*

$$SPOP = INTEG(CSP, pPOP) \tag{D.73}$$

The past population is smoothed over a 3 year period as well, to remove some of the high frequency noise from the signal before it is used to calculate the growth rate, which will then be used to project population.

(TAL) Time to Average Loss Rate, *Year*

$$TAL = 1 \tag{D.74}$$

The smoothing time for (EL) Expected Loss Rate. In this case, the actual (LR) Unit Demolition Rate is a very smooth signal, so we use a relatively short smoothing time here.

(TAOD*) Time to Adjust Desired Occupant Density, *Year*

$$TAOD* = 1.5 \tag{D.75}$$

Occupants adjust their opinions about appropriate occupant density relatively quickly, so a value of 1.5 years is estimated for this parameter.

(URP) Fractional Sublet Rate, *1/Year*

$$URP = ASR + USR \tag{D.76}$$

The fractional rate at which units are transferred from ownership to whole-unit, non-resident sublet status. This is the sum of Approved Sublets and Unapproved Sublets.

(USR) Unapproved Sublet Rate, *1/Year*

$$USR = ASR \tag{D.77}$$

Given the limited number of sublet approvals, it is assumed that some public unit owners who have vacated their units (either through purchase of a private unit, elderly owners moving in with their children, or relocation to another country) will choose to retain ownership of the unit, and sublet it out to non-residents without HDB approval. The assumption here is that this quantity is equal to the (ASR) Approved Sublet Rate.

(FINALTIME), *Year*

$$FINALTIME = 2011 \tag{D.78}$$

The final time for the simulation.

(INITIALTIME), *Year*

$$INITIALTIME = 1990 \tag{D.79}$$

The initial time for the simulation.

(SAVEPER), *Year[0,?]*

$$SAVEPER = 0.25 \tag{D.80}$$

The frequency with which output is stored.

(TIMESTEP), *Year[0,?]*

$$TIMESTEP = 0.0625 \tag{D.81}$$

The time step for the simulation.

Appendix E

Model Input Data

Sheet:	Land Use Data	Land Use Data	Land Use Data	Land Use Data	Land Use Data	Land Use Data
Column:	C	D	F	G	I	J
Time	**(HCD) HDB Unit Completion DATA**	**(HSD) HDB Unit Stock DATA**	**(NCD) Non-Landed Unit Completion DATA**	**(NSD) Non-Landed Unit Stock DATA**	**(LCD) Landed Unit Completion DATA**	**(LSD) Landed Unit Stock DATA**
Year	*units/year*	*units*	*units/year*	*units*	*units/year*	*units*
1990.00	12,693	615,010	1,904	61,497	1,743	50,483
1991.00	11,337	627,165	1,602	63,401	1,918	52,226
1992.00	16,564	627,812	2,323	65,169	1,272	54,249
1993.00	22,023	642,985	3,957	68,120	1,963	55,680
1994.00	24,597	661,216	5,718	71,398	1,309	57,371
1995.00	26,977	680,963	5,180	76,899	1,545	58,583
1996.00	28,519	705,771	5,750	81,799	2,361	59,796
1997.00	32,800	732,022	11,665	87,520	2,917	61,594
1998.00	33,340	763,707	12,131	98,042	1,907	63,231
1999.00	35,694	795,888	9,654	109,315	1,425	64,258
2000.00	26,159	828,215	9,514	118,575	1,297	64,976
2001.00	21,845	849,489	6,067	127,001	750	66,027
2002.00	10,862	862,918	6,957	132,142	773	66,212
2003.00	9,084	868,774	5,957	138,707	662	66,490
2004.00	6,164	875,887	10,619	143,842	1,180	67,092
2005.00	4,378	879,566	7,827	154,265	870	67,638
2006.00	1,764	879,092	5,868	161,410	652	67,946
2007.00	6,247	878,813	5,862	164,954	651	68,410
2008.00	1,769	885,140	9,110	166,352	1,012	68,460
2009.00	7,050	883,896	9,439	172,443	1,049	68,761
2010.00	11,888	890,212	9,359	179,991	1,040	69,498
2011.00		901,971		188,500		69,743

Sheet:	Quarterly Data	Quarterly Data	Quarterly Data	Quarterly Data	Past Data
Column:	F	S	V	Y	D
Time	**(PD) Price Index DATA**	**(ORD) Unit Initiation Rate DATA**	**(SD) Unit Stock DATA**	**(POP) Population DATA**	**(pPOP) Past Population DATA**
Year	*dmnl*	*units/year*	*units*	*people*	*people*
1990.00	44.9	19,168	727,010	3,047,100	2,774,800
1990.25	46.0				
1990.50	46.1				
1990.75	46.5				
1991.00	45.1	26,702	742,792	3,135,100	2,846,100
1991.25	45.7				
1991.50	47.1				
1991.75	46.8				
1992.00	46.5	36,858	747,230	3,230,700	2,930,900
1992.25	47.9				
1992.50	50.1				
1992.75	51.2				
1993.00	52.1	37,611	766,785	3,313,500	3,047,100
1993.25	54.7				
1993.50	67.9				
1993.75	79.0				
1994.00	81.5	47,650	789,985	3,419,000	3,135,100
1994.25	84.6				
1994.50	88.9				
1994.75	94.8				
1995.00	95.1	51,634	816,445	3,524,500	3,230,700
1995.25	98.3				
1995.50	106.0				
1995.75	110.3				
1996.00	118.2	48,013	847,366	3,670,700	3,313,500
1996.25	126.9				
1996.50	140.2				
1996.75	145.2				
1997.00	146.7	48,842	881,136	3,796,000	3,419,000
1997.25	144.2				
1997.50	142.0				
1997.75	135.5				
1998.00	127.4	32,408	924,980	3,927,200	3,524,500
1998.25	117.7				
1998.50	111.7				
1998.75	104.7				
1999.00	100.0	27,708	969,461	3,958,700	3,670,700

Sheet:	Quarterly Data	Quarterly Data	Quarterly Data	Quarterly Data	Past Data
Column:	F	S	V	Y	D
Time	**(PD) Price Index DATA**	**(ORD) Unit Initiation Rate DATA**	**(SD) Unit Stock DATA**	**(POP) Population DATA**	**(pPOP) Past Population DATA**
Year	*dmnl*	*units/year*	*units*	*people*	*people*
1999.25	99.9				
1999.50	103.5				
1999.75	111.9				
2000.00	115.2	20,430	1,011,766	4,027,900	3,796,000
2000.25	116.2				
2000.50	115.0				
2000.75	112.0				
2001.00	109.0	16,981	1,042,517	4,138,000	3,927,200
2001.25	104.8				
2001.50	103.1				
2001.75	100.6				
2002.00	98.2	10,798	1,061,272	4,176,000	3,958,700
2002.25	97.4				
2002.50	97.5				
2002.75	98.4				
2003.00	98.4	12,486	1,073,971	4,114,800	4,027,900
2003.25	99.3				
2003.50	100.7				
2003.75	102.4				
2004.00	103.2	8,996	1,086,821	4,166,700	4,138,000
2004.25	102.8				
2004.50	103.4				
2004.75	103.1				
2005.00	103.7	13,502	1,101,469	4,265,800	4,176,000
2005.25	103.8				
2005.50	99.9				
2005.75	99.8				
2006.00	100.3	14,700	1,108,448	4,401,400	4,114,800
2006.25	100.5				
2006.50	101.4				
2006.75	101.7				
2007.00	103.1	22,540	1,112,177	4,588,600	4,166,700
2007.25	104.7				
2007.50	108.6				
2007.75	115.6				
2008.00	121.9	28,993	1,119,952	4,839,400	4,265,800
2008.25	124.4				

Sheet:	Quarterly Data	Quarterly Data	Quarterly Data	Quarterly Data	Past Data
Column:	F	S	V	Y	D
Time	**(PD) Price Index DATA**	**(ORD) Unit Initiation Rate DATA**	**(SD) Unit Stock DATA**	**(POP) Population DATA**	**(pPOP) Past Population DATA**
Year	*dmnl*	*units/year*	*units*	*people*	*people*
2008.50	126.5				
2008.75	127.7				
2009.00	125.2	20,230	1,125,100	4,987,600	4,401,400
2009.25	120.3				
2009.50	120.3				
2009.75	127.2				
2010.00	132.9	37,147	1,139,701	5,076,700	4,588,600
2010.25	136.4				
2010.50	141.3				
2010.75	145.7				
2011.00	148.4		1,160,214	5,183,700	4,839,400
2011.25					
2011.50					

Appendix F

Housing and Development Board Correspondence

From: Asri MD MAAROF, am2@hdb.gov.sg

Subject: SINGAPORE HOUSING RESEARCH

Date: January 25, 2012 3:18:28 AM EST

To: Noel Davis, nrdavis@mit.edu

> HOUSING & DEVELOPMENT BOARD
>
> SINGAPORE HOUSING RESEARCH
>
> Your Ref :
>
> Our Ref :
>
> Date : 25 Jan 2012
>
> TEL : 64903592
>
> FAX : 64903588
>
> EMAIL : am2@hdb.gov.sg

Dear Mr Noel Davis,

Thank you for your e-mail of 12 January 2012. We apologise for taking a longer time to reply as we need to seek input from the relevant department. The following are the answers to your questions:

1. How does the HDB decide how many housing units to initiate at any given time? What indicators are most important in determining the quantity of new housing starts (resale price index, population, housing applications, etc)? How does the HDB attempt to anticipate future demand for housing units?

> HDB plans its new flat supply based on demand and supply that is sustainable for the entire housing market, taking into account overall population growth (including marriages and migration), as well as resale flats released into the market by those moving out of public housing (e.g. through deaths, emigration, and upgrading by existing home owners to private properties) which will be available to meet part of the new demand. After accounting for what is met through the resale market, HDB then builds new flats to meet net housing needs.
>
> Housing demand in the short term could fluctuate depending on population and economic dynamics. Home buyers will adjust their purchases, depending on the economic outlook and market sentiments. Therefore, HDB regularly reviews its flat supply and make short-term adjustments in response to the prevailing market conditions, through a mix of demographic, economic and housing market indicators which are read in totality rather than each on its own.

2. How long does the HDB plan for between initiation of new housing units, and their occupation? What is the total average time for planning, constructing, completing and occupying a new HDB unit?

> Build-To-Order (BTO) flats will typically take about 2.5 years to be completed.

3. Does the HDB take non-residents into account when planning for its future growth and development? If yes, how?

> Non-residents are taken into consideration when planning for future development, but not all are considered when measuring demand for HDB flats because (i) there are restrictions on public housing ownership - non-residents are not allowed to own HDB flats but can sublease whole flats or rent rooms from HDB flat owners, which will be taken into account; and (ii) some non-residents may have other accommodation arrangements, e.g. dormitories.

3a. Are non-residents eligible to sublease whole units when approved by the HDB, or is this sublease only available to permanent residents and citizens?

> We gather that you are asking on whether non-citizens can rent a flat from existing HDB flat owners. Singapore citizens, Singapore permanent residents and non-citizens may rent a flat from existing HDB flat owners under the Subletting of Flat Scheme.

4. How involved is the HDB in setting/influencing prices in the public resale housing market?

> HDB does not set the price of flats transacted in the resale market. The price of such flat is negotiated between willing buyers and sellers. Notwithstanding this, the Government takes active steps to facilitate homeownership in various fronts. In the last 2 years, the major thrust of the policy measures was to help first-time home buyers own a home. The measures were designed to stabilize and ensure a sustainable public housing market. For example, in 2010, the Government announced a series of measures to curb the buoyant resale public housing market. Amongst which were measures to reinforce owner occupation of HDB flats, facilitate right-sizing and encourage financial prudence.

5. How does HDB anticipate and account for the contributions of private housing when making future decision on how many units to provide?

> HDB adopts a holistic approach in projecting housing demand. As mentioned in the response to Q1, we plan the supply based on what is sustainable for entire housing market, which incorporates private housing as well. The supply planned for public housing is thus based on net demand for the public housing sector.

Yours sincerely,

ASRI MD MAAROF

SENIOR ADMIN EXECUTIVE

CUSTOMER SERVICES CENTRE

ESTATE ADMINISTRATION & PROPERTY DEPARTMENT

Bibliography

[1] United Nations Department of Economic and Social Affairs/Population Division, *World urbanization prospects: The 2009 revision.* United Nations Publications, 2010.

[2] E. Glaeser, *Triumph of the City: How Our Greatest Invention Makes Us Richer, Smarter, Greener, Healthier, and Happier*. Penguin Press, 2011.

[3] K. Steemers, “Energy and the city: density, buildings and transport,” *Energy and buildings*, vol. 35, no. 1, pp. 3–14, 2003.

[4] L. Hordijk, “Use of the rains model in acid rain negotiations in europe,” *Environmental science & technology*, vol. 25, no. 4, pp. 596–603, 1991.

[5] W. Tuinstra, L. Hordijk, and M. Amann, “Using computer models in international negotiations- the case of acidification in europe,” *Environment(Washington DC)*, vol. 41, no. 9, pp. 33–42, 1999.

[6] W. Tuinstra, L. Hordijk, and C. Kroeze, “Moving boundaries in transboundary air pollution co-production of science and policy under the convention on long range transboundary air pollution,” *Global Environmental Change*, vol. 16, no. 4, pp. 349–363, 2006.

[7] F. Krausmann, “Land use and industrial modernization: an empirical analysis of human influence on the functioning of ecosystems in austria 1830-1995,” *Land use policy*, vol. 18, no. 1, pp. 17–26, 2001.

[8] F. Krausmann, M. Fischer-Kowalski, H. Schandl, and N. Eisenmenger, “The global sociometabolic transition,” *Journal of Industrial Ecology*, vol. 12, no. 5-6, pp. 637–656, 2008.

[9] R. Corlett, “The ecological transformation of singapore, 1819-1990,” *Journal of Biogeography*, vol. 19, no. 4, pp. 411–420, 1992.

[10] M.T.I., *Growing our economy.* Ministry of Trade and Industry, http://app.mti.gov.sg/default.asp?id=487, April 2012.

[11] A. Arulrajah, *Field Measurements and Back-Analysis of Marine Clay Geotechnical Characteristics under Reclamation Fills.* PhD thesis, Curtin

University of Technology, http://adt.curtin.edu.au/theses/available/adt-WCU20050729.101614/unrestricted/, 2005.

[12] T. Wong and A. Yap, *Four decades of transformation: land use in Singapore, 1960-2000.* Eastern University Press, 2004.

[13] S. Teo and V. Savage, "Singapore landscape: a historical overview of housing change," *Singapore Journal of Tropical Geography*, vol. 6, no. 1, pp. 48–63, 1985.

[14] D.O.S., *Yearbook of Statistics Singapore.* Department of Statistics, Ministry of Trade & Industry, 1960–2011.

[15] S. Teo, "Patterns of change in public housing in singapore," *Third World Planning Review*, vol. 11, no. 4, p. 373, 1989.

[16] S. Lum, "Market fundamentals, public policy and private gain: house price dynamics in Singapore," *Journal of Property Research*, vol. 19, no. 2, pp. 121–143, 2002.

[17] Y. Tu and G. Wong, "Public policies and public resale housing prices in Singapore," *International Real Estate Review*, vol. 5, no. 1, pp. 115–132, 2002.

[18] H.D.B., *Annual Report.* Housing & Development Board, Ministry of National Development, 1960–2011.

[19] X. Bai, "Industrial ecology and the global impacts of cities," *Journal of Industrial Ecology*, vol. 11, no. 2, pp. 1–6, 2007.

[20] D. E. Bloom, D. Canning, and G. Fink, "Urbanization and the wealth of nations," *Science*, vol. 319, no. 5864, p. 772, 2008.

[21] S. Erkman, "Industrial ecology: an historical view," *Journal of cleaner production*, vol. 5, no. 1, pp. 1–10, 1997.

[22] R. Ayres, L. Ayres, and P. Frankl, *Industrial ecology: towards closing the materials cycle.* Edward Elgar Cheltenham, 1996.

[23] A. Wolman, "The metabolism of the city," *Scientific American*, vol. 213, no. 3, pp. 178–193, 1965.

[24] P. L. Daniels and S. Moore, "Approaches for quantifying the metabolism of physical economies: Part i: Methodological overview," *Journal of Industrial Ecology*, vol. 5, no. 4, pp. 69–93, 2001.

[25] P. L. Daniels, "Approaches for quantifying the metabolism of physical economies: A comparative survey: Part II: review of individual approaches," *Journal of Industrial Ecology*, vol. 6, no. 1, pp. 65–88, 2002.

[26] S. Niza, L. Rosado, and P. Ferrão, "Urban metabolism," *Journal of Industrial Ecology*, vol. 13, no. 3, pp. 384–405, 2009.

[27] C. Kennedy, J. Cuddihy, and J. Engel-Yan, "The changing metabolism of cities," *Journal of Industrial Ecology*, vol. 11, no. 2, pp. 43–59, 2007.

[28] F. Krausmann, S. Gingrich, N. Eisenmenger, K. Erb, H. Haberl, and M. Fischer-Kowalski, "Growth in global materials use, gdp and population during the 20th century," *Ecological Economics*, vol. 68, no. 10, pp. 2696–2705, 2009.

[29] N. Schulz, "Contributions of material and energy flow accounting to urban ecosystem analysis: Case study singapore," 2005. United Nations University, Institute of Advanced Studies working paper 136. Yokohama: UNU. ¡www.ias.unu.edu/publications/iaswp.cfm¿. Accessed October 2010.

[30] N. Schulz, "Socio-economic development and society's metabolism in singapore," 2006. United Nations University, Institute of Advanced Studies working paper 148. Yokohama: UNU. ¡www.ias.unu.edu/publications/iaswp.cfm¿. Accessed October 2010.

[31] H. Rechberger, *Practical Handbook of Material Flow Analysis*. CRC Press, 1 ed., Oct. 2003.

[32] M. Fischer-Kowalski, "Societys metabolism: The intellectual history of material flows analysis, part 1: 1860–1970," *Journal of Industrial Ecology*, vol. 2, no. 1, pp. 61–78, 1998.

[33] M. Fischer-Kowalski and W. Huttler, "Societys metabolism, the intellectual history of materials flow analysis, part ii, 1970–1998," *Journal of Industrial Ecology*, vol. 2, no. 4, pp. 107–136, 1999.

[34] Eurostat, H. Schutz, and A. Steurer, *Economy-wide material flow accounts and derived indicators: a methodological guide*. Office for Official Publications of the European Communities, 2001.

[35] S. Bringezu, H. Schutz, S. Steger, and J. Baudisch, "International comparison of resource use and its relation to economic growth:: The development of total material requirement, direct material inputs and hidden flows and the structure of tmr," *Ecological economics*, vol. 51, no. 1-2, pp. 97–124, 2004.

[36] E. Matthews, C. Amann, S. Bringezu, W. Hüttler, C. Ottke, E. Rodenburg, D. Rogich, H. Schandl, E. Van, D. Voet, *et al.*, "The weight of nations: Material outflows from industrial economies," in *World Resources Institute*, 2000.

[37] A. Smith, *Wealth of nations: the economics classic*. Capstone, 2010.

[38] J. E. Fernández, "Resource consumption of new urban construction in china," *Journal of Industrial Ecology*, vol. 11, no. 2, pp. 99–115, 2007.

[39] D. J. Quinn, "Modeling the resource consumption of housing in New Orleans using System Dynamics," Master's thesis, Massachusetts Institute of Technology, 2008.

[40] K. N. Welling, "Modeling the water consumption of Singapore using system dynamics," Master's thesis, Massachusetts Institute of Technology, 2011.

[41] B. F. Forward and I. of Wastes Management (Great Britain). Environmental Body, *City Limits: A resource flow and ecological footprint analysis of Greater London.* Best Foot Forward, 2002.

[42] N. B. Schulz, "The direct material inputs into singapore's development," *Journal of Industrial Ecology*, vol. 11, no. 2, pp. 117–131, 2007.

[43] B. Muller, "Stock dynamics for forecasting material flows–case study for housing in the Netherlands," *Ecological Economics*, vol. 59, no. 1, pp. 142–156, 2006.

[44] H. Bergsdal, H. Brattebø, R. Bohne, and D. Müller, "Dynamic material flow analysis for Norway's dwelling stock," *Building Research & Information*, vol. 35, no. 5, pp. 557–570, 2007.

[45] M. Hu, E. V. D. Voet, and G. Huppes, "Dynamic material flow analysis for strategic construction and demolition waste management in beijing," *Journal of Industrial Ecology*, vol. 14, no. 3, pp. 440–456, 2010.

[46] T. Abou-Abdo, N. Davis, J. Krones, K. Welling, and J. Fernandez, "Dynamic modeling of Singapore's urban resource flows: Historical trends and sustainable scenario development," in *2011 IEEE International Symposium on Sustainable Systems and Technology (ISSST)*, pp. 1–6, 2011.

[47] H. Selin and N. Eckley, "Science, politics, and persistent organic pollutants: The role of scientific assessments in international environmental co-operation," *International Environmental Agreements: Politics, Law and Economics*, vol. 3, no. 1, pp. 17–42, 2003.

[48] F. Schmidt-Bleek, "Mips. a universal ecological measure?.," *Fresenius environmental bulletin*, vol. 2, no. 6, pp. 306–311, 1993.

[49] M. Wackernagel and W. Rees, *Our ecological footprint: reducing human impact on the earth*, vol. 9. New Society Publishers, 1996.

[50] B. Ewing and G. F. Network, *The ecological footprint atlas 2010.* Global Footprint Network, 2010.

[51] J. van den Bergh and H. Verbruggen, "Spatial sustainability, trade and indicators: an evaluation of the ecological footprint'," *Ecological Economics*, vol. 29, no. 1, pp. 61–72, 1999.

[52] J. Kitzes, A. Galli, M. Bagliani, J. Barrett, G. Dige, S. Ede, K. Erb, S. Giljum, H. Haberl, C. Hails, *et al.*, "A research agenda for improving national ecological footprint accounts," *Ecological Economics*, vol. 68, no. 7, pp. 1991–2007, 2009.

[53] T. Wiedmann, J. Minx, J. Barrett, and M. Wackernagel, “Allocating ecological footprints to final consumption categories with input-output analysis,” *Ecological Economics*, vol. 56, no. 1, pp. 28–48, 2005.

[54] R. Coyle, *System dynamics modelling: A practical approach*. London: Chapman & Hall, 1996.

[55] J. Forrester, *Industrial Dynamics*. MIT Press, Cambridge, MA, 1961.

[56] J. Forrester, *Urban Dynamics*. Cambridge, MA: MIT Press, 1969.

[57] L. Alfeld, “Urban dynamics the first fifty years,” *System Dynamics Review*, vol. 11, no. 3, pp. 199–217, 1995.

[58] J. Richardson and O. Elizabeth, “The relevance of urban dynamics to singapore’s success story: lessons for moving beyond the crisis.” Presented at the 28th International Systems Dynamics Conference, Seoul, South Korea, July 2010.

[59] J. Forrester, *World dynamics*. Cambridge, MA: Wright-Allen Press, 1971.

[60] D. Meadows, D. Meadows, J. Randers, W. Behrens, and R. C. of, *The limits to growth*, vol. 205. Universe Books New York, 1972.

[61] E. Keating, “Everything you ever wanted to know about how to develop a system dynamics model, but were afraid to ask,” in *16th International Conference of the System Dynamics Society 1998*, 1998.

[62] J. Hines, “Molecules of structure, version 2.02, building blocks for system dynamics models,” *Software documentation. LeapTec and Ventana Systems Inc.: available at: http:///www. vensim. com//molecule. html (11 November 2005)*, 2005.

[63] H.D.B., *Selective En-Bloc Redevelopment Scheme*. Singapore Housing Development Board, http://www.hdb.gov.sg/fi10/fi10329p.nsf/w/eSERSOverview?OpenDocument, March 2012.

[64] J. D. Sterman, *Business dynamics: systems thinking and modeling for a complex world. 2000*. Boston: Irwin, 2000.

[65] U.R.A., *Private Residential Property Transactions with Caveats Lodged*. Singapore Urban Redevelopment Authority, www.ura.gov.sg/realEstateWeb/realEstate/pageflow/transaction/TransactionController.jpf, October 2011.

[66] T. Wong and A. Yap, “From universal public housing to meeting the increasing aspiration for private housing in Singapore,” *Habitat International*, vol. 27, no. 3, pp. 361–380, 2003.

[67] M. Pont and P. Haupt, “The spacemate: density and the typomorphology of the urban fabric,” *Nordic Journal of Architectural Research*, vol. 4, pp. 55–68, 2005.

[68] K. S. Leung, "Rediscovering urban vernacular for high-density housing in the tropics." The Martin Centre for Architectural and Urban Studies, Department of Architecture, the University of Cambridge, 2009.

[69] U.R.A., "Singapore master plan 2008," tech. rep., Urban Redevelopment Authority, 2008.

[70] K. Addae-Dapaah, "Utilization of urban residential land: a case study of Singapore," *Cities*, vol. 16, no. 2, pp. 93–101, 1999.

[71] H.D.B., *Sale of Sites, Land Sales Data*. Singapore Housing Development Board, www.hdb.gov.sg/fi10/fi10330p.nsf/w/LandDevMangSitesForSale?OpenDocument, October 2011.

[72] U.R.A., *Sale of Sites, Land Sales Data*. Singapore Urban Redevelopment Authority, www.ura.gov.sg/sales/landsales.htm, October 2011.

[73] S.L.A., *Sale of Sites, Land Sales Data*. Singapore Land Authority, www.sla.gov.sg/Land_Sales/ls_index.htm, October 2011.

[74] A. Deo Bardhan, R. Datta, R. Edelstein, and L. Sau Kim, "A tale of two sectors: Upward mobility and the private housing market in Singapore* 1," *Journal of Housing Economics*, vol. 12, no. 2, pp. 83–105, 2003.

[75] S. Ong and T. Sing, "Price discovery between private and public housing markets," *Urban Studies*, vol. 39, no. 1, p. 57, 2002.

[76] S. Phang and W. Wong, "Government policies and private housing prices in Singapore," *Urban studies*, vol. 34, no. 11, p. 1819, 1997.

[77] T. Sing, I. Tsai, *et al.*, "Price dynamics in public and private housing markets in Singapore," *Journal of Housing Economics*, vol. 15, no. 4, pp. 305–320, 2006.

[78] E. Glaeser, J. Gyourko, and A. Saiz, "Housing supply and housing bubbles," *Journal of Urban Economics*, vol. 64, no. 2, pp. 198–217, 2008.

[79] D. Meadows, *Dynamics of commodity production cycles*. Wright-Allen Press, 1970.

[80] Y. Lee, "Determinants of Singapore residential land value," Master's thesis, Massachusetts Institute of Technology, 2002.

[81] J. Chan, "Ramped up supply of BTO flats easing market imbalance," *Channel New Asia*, October 23, 2011.

[82] O. D. Lin, "More HDB flats and new towns planned to ease housing crunch," *Today Online*, October 13, 2011.

[83] C. Ong, "More than 17,000 bids for HDB's 'leftover' flats," *Straits Times*, September 29, 2011.

[84] E. Teo, "Housing glut 'won't cause dip in prices': Property expert," *Straits Times*, September 14, 2011.

[85] D. Phillips and H. Bartlett, "Aging trends–Singapore," *Journal of Cross-Cultural Gerontology*, vol. 10, no. 4, pp. 349–356, 1995.