Dynamics of polycentric urban structure

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הוגש לסנט הטכניון - מכון טכנולוגי לישראל

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המחקר נעשה בהנחיית

פרופ' דניאל צ'מנסקי
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פרופ' יצחק בננסון
אוניברסיטת תל-אביב

בפקולטה לארכיטקטורה ובינוי ערים

אני מודה לטכניון – המכון הטכנולוגי לישראל על התמיכה הכספית הנדיבה בהשתלמותי

Abstract:

Classical urban models explain the spatial structure of an ideal mono-centric city assuming the pre-existence of a Central Business District (CBD). These models are driven by demand for geographic locations in proximity to the CBD. They lead to monotonically decreasing land rents and density as the distance from the CBD increases. However, modern cities can be considered to be mono-centric at a very crude geographic resolution only. Processes of urban growth typically give rise to a poly-centric structure. There is a growing body of evidence that urban spatial dynamics are discontinuous in space and non-uniform in time. Moreover, the speed of spatial expansions in some cities displays irregular patterns in different zones. The classical urban economics models are hard pressed to explain the formation of modern cities with polycentric structure and the dynamic processes that characterize them. Their inherent equilibrium based framework combined with a demand side focus, which ignores the supply side, is an impediment for understanding essentially dynamic processes.

Several factors are at the backdrop of polycentric urban evolution. Land developers' choices in a context of spatial restrictions imposed by city planners lead to outcomes different than those forecasted by classical models. Attraction exerted by proximate, competing cities, combined with land development policies and developers' behavior results in other types of urban development. In addition, assuming heterogeneous actors, such as developers with varying degrees of risk aversion, lead to complex urban spatial structures. The concept of characteristic time, defined as the period of time from the acquisition of initial property rights in the land by developers and until the first return on the investment is realized, captures spatial policy settings within which developers operate.

The set of models included here offers an explanation for the emergence of ideal polycentric cities and their associated dynamics. The models are focused on the supply side of the urban market and its interactions with city's planning policies. When it is possible and tractable, a comparative static's approach is presented. However, most of the analysis is by means of agent-based modeling approach. The research demonstrate that the adversarial interactions between real estate developers and makers of planning policies create out-of-equilibrium, non-linear urban dynamics characterized by sudden emergence of sub-centers. A hypothesis is proposed that at the urban scale, the complex dynamics that emerge in the models cause patterns similar to those created by Self Organizing Criticality models, studied extensively in the exact sciences.

תקציר:

המודלים הקלאסיים בכלכלה עירונית מתארים התפתחות מרחבית של עיר אידיאלית סביב מרכז עסקים ראשי (מע"ר) יחיד. היות והפעילות הכלכלית מתרכזת במע"ר, האזורים בסביבתו הקרובה הם המבוקשים ביותר. ככל שמתרחקים ממנו, הנכונות של פירמות ופרטים לשלם עבור הקרקע הולכת ודועכת. גורם שמצליח לשלם יותר עבור הקרבה למע"ר זוכה בתחרות ודוחק אחרים החוצה, אל מקומות יותר מרוחקים. כתוצאה מכך המודל צופה ירידה מונוטונית בערך המקרקעין וצפיפות הבנייה ככל שמתרחקים מהמרכז. אולם, חלק נכבד מהערים המודרניות אינן יכולות להיחשב עוד חד-מוקדיות (מונוצנטריות). בערים רבות ניתן לאתר מספר רב של מוקדי משנה המרכזים חלק גדל והולך מהפעילות הכלכלית. ניתן לומר שתהליכים של התפתחות עירונית מולידים בדרך כלל מבנה עירוני רב-מוקדי. יתר על כן, ממצאים אמפיריים מצביעים על דינאמיקה עירונית בלתי רציפה הן במימד במרחבי והן במימד הזמן. המודלים הקלאסיים של כלכלה עירונית מתקשים להתמודד עם תופעות אלו. דבקותם במסגרת רעיונית של שיווי משקל כללי, יחד עם דגש על התנהגות צד הביקוש בלבד, מהווים מכשול להבנת תהליכים שהם דינאמיים בעיקרם.

ניתן למנות מספר גורמים אשר עומדים מאחורי תהליכים המובילים להתפתחות רב-מוקדית של ערים. הגורם הראשון נובע מהתנהגותם של יזמי נדל"ן באופן כללי, ובפרט תחת אילוצים המוכתבים על ידי רשויות התכנון העירוני והרגולציה המוטלת על שימושי קרקע. כוחות המשיכה של ערים שכנות המתחרות ביניהן (או לעיתים משתפות פעולה), מהווה גורם נוסף. שילוב זה, של אילוצי תכנון ותגובות יזמי נדל"ן המנסים להשיא את רווחיהם, יוצר צורות מרחביות חדשות בהתפתחותה של העיר. גורם שלישי הוא ההטרוגניות של השחקנים במגרש העירוני. ניתן להניח שיזמי נדל"ן נבדלים ביניהם בנכונותם ליטול סיכונים בפרויקטים. כתוצאה מכך, תגובתו של כל יזם לנוכח אילוץ מסוים תיגזר מנכונותו לסכן את השקעתו. במסגרת זו, ניתן להגדיר את המושג "זמן אופייני" כפרק הזמן העובר בין רכישת זכויות בקרקע על ידי יזם ועד לקבלת אישור הבנייה. הבדלים מרחביים בזמן האופייני מגדירים את הסביבה התכנונית בה היזמים פועלים. התנהגות של יזמים הטרוגניים לנוכח זמן אופייני המשתנה ממקום למקום, עשויה לכן, להוליד מבנים עירוניים מורכבים.

גישה ראשונה לבחינת הבעיה מבוססת על המקרה של שתי רשויות הנמצאות במרחב ליניארי. רשויות אלו מגדירות מדיניות פיתוח שבאה לידי ביטוי בקביעת זמן אופייני שונה בתחום השיפוט שבאחריותן. מדיניות הפיתוח משקפת את החזון התכנוני של כל אחת מהרשויות, אולם גם מושפעת מההעדפות של גורמים נוספים הפועלים בהן, כגון קבוצות לחץ וארגונים לא ממשלתיים. התנהגות קצרת-ראות מוגדרת כמצב שבו שכל רשות מעוניינת אך ורק במה שמתרחש בשטחה. התנהגות זו יכולה להוביל בקלות לתבנית פיתוח מבוזרת ולא מתוכננות. תוצאה זו מתקבלת בגלל היעדר תאום מרחבי בין הרשויות, במיוחד באזור הגבול המוניציפאלי המשותף ביניהם. מאידך, תחרות בין הרשויות, בהנחה שכל אחת מהן מודעת לתהליכים המתרחשים בכל האזור (לא רק בשטח השיפוט שלה) יכולה להוביל ל-"קפיצות צפרדע" או לריכוז הפיתוח העירוני קרוב למרכז העסקי, בהתאם למדיניות הננקטת על ידי כל אחד מהרשויות. במקרה זה הפיתוח האורבאני בכל המרחב הליניארי מאופיין על ידי המטרות וגודל שטח השיפוט של כל אחת הרשויות.

נוסף על כך, נבחן מודל בו קיימים סוגים שונים של רשויות, כמו למשל כרך מבוסס מול עיר קטנה. א-סימטריה בגודלן ובעוצמתן של הערים מגדירה במרחב שביניהם כוחות משיכה המשפיעים על הנכונות לשלם עבור דיור בכל נקודה בתווך. המיקום היחסי של הגבול המוניציפאלי וכוחות המשיכה הכלכליים הפועלים מעבר לשטחי השיפוט של כל רשות יוצרים תרחישים מגוונים עבור יזמים המחפשים להשיא את רווחיהם. לתרחישים הנוצרים בגין מטרות פיתוח מגוונות, שכבר נבחנו במודל הקודם, מתווספים הפעם גורמים נוספים ורבי עוצמה. מכוון שכוחות המשיכה של כל רשות לא בהכרח מותאמים לשטח השיפוט שלהן, נוצרים מצבים בהם הנכונות לשלם עבור דיור במקום מסוים בתחום רשות אחת, מושפעת מהקרבה היחסית לרשות האחרת. לכן השילוב בין מדיניות התכנון של כל עיר, העוצמה היחסית שלהן, השפעתה המרחבית של עוצמה זו, והמיקום של הגבול המוניציפאלי, יוצרים אפשרויות רבות לאורך כל המרחב הליניארי. שיקולי היזמים במציאות מרחבית מורכבת זו, יוצרים מגוון תבניות להתפתחות אורבאנית, מריכוז הפיתוח סביב המרכזים העירוניים ועד לקפיצות צפרדע ופיתוח מבוזר.

הגישה השנייה לניתוח הדינאמיקה העירונית והופעתם של מרכזים עירוניים משניים מושתתת על מודל Cellular Automata בשילוב עם מודל מבוסס סוכנים (Agent-Based model). השימוש המשותף של כלים אלו, מאפשר גמישות רבה באפיון השחקנים הפועלים במודל. באמצעות מספר מצומצם של סוכנים, המייצגים את הרשות העירונית ויזמי נדל"ן הפועלים בשטחה, ניתן לבצע סימולאציות להתפתחות עירונית במרחב כפועל יוצא של יחסי הגומלין ביניהם. יתר על כך, ניתן לנתח את ביצועי הסימולאציה לאורך זמן ולבחון את רגישותה לשינויים בפרמטרים ובאפיון הסוכנים.

במודל זה העיר מוגדרת כרשת ריבועית של חלקות קרקע, כאשר כל חלקה מאופיינת על ידי מספר פרמטרים. לכל חלקה המודל מתאים זמן האופייני משלה, ערך הקרקע, הנכונות לשלם עבור נכס במקום והמצב הנוכחי שלה (חלקה פנויה, חלקה שממתינה לאישור פיתוח או חלקה בנויה). כל אחד מהפרמטרים הללו משתנה לאורך זמן בהתאם לשינויים בשוק, למדיניות הפיתוח ולשינויים מרחביים החלים בסביבה. ברקע, אוכלוסיית העיר ההולכת וגדלה מייצגת את הביקוש למוצרי נדל"ן. הקונפיגורציה של כל החלקות בעיר בזמן נתון והביקוש הקיים מגדירים את סביבת הפעילות של כל הסוכנים במודל.

אחד הסוכנים היא הרשות העירונית בעצמה. היא מגדירה את הזמן האופייני המתאים לכל חלקה על פי מדיניות של ריכוז הפיתוח האורבאני קרוב ככל האפשר ממרכז העסקים הראשי. כתוצאה מכך פונקציית הזמן האופייני עולה ככל שמתרחקים ממרכז העיר. אם זאת, הרשות מתאפיינת גם בגמישות תכנונית, במידה ותנאי המרחב והשוק דורשים זאת. כאשר ההיצע בשוק נמוך מדי בגלל מגבלות תכנוניות, הרשות יכולה לשנות את פונקצית הזמן האופייני באזור מסוים על מנת לאפשר את המשך הפיתוח האורבאני. מידת ההיענות של העירייה ללחצים הקיימים והעיתוי של התגובה הם פונקציה של הביקוש הקיים והפעולות של הסוכנים הנוספים, היזמים.

יזמי נדל"ן נבדלים ביניהם בנכונות לחכות מרגע רכישת הזכויות בקרקע עד להשלמת הפרויקט וקבלת התקבולים בגינו. יזמים לא-סבלניים מחפשים הזדמנויות רק בחלקות שהזמן האופייני שלהם קצר. לעומתם, יזמים סבלניים, שהם בדרך כלל בעלי יכולות פיננסיות גדולות יותר, אינם מוגבלים על ידי הזמן האופייני. יתרה מכך, אותם יזמים סבלניים מסוגלים לייצר הזדמנויות לפיתוח בחלקות מרוחקות מליבת העיר. כאשר חלקות קרקע זמינות בעלות זמן אופייני קצר הולכות ומתמעטות, יזמים סבלניים פונים לחיפוש אחר חלקות זמינות בשולי העיר. בגלל יתרונות לגודל והגדלת הסיכוי לקבל אישורי בנייה, יזמים סבלניים נוטים לרכז מאמצים באזורים ממוקדים. כאשר רשויות התכנון מחליטות לאפשר את המשך הפיתוח האורבאני (באמצעות שינוי בזמן האופייני), יש סיכוי רב שזה יקרה במקומות בהם קיים ריכוז של קרקעות אשר נרכשו על ידי יזמים סבלניים מבעוד מועד.

באזור הנבחר על ידי הרשות להמשך הפיתוח העירוני פונקצית זמן אופייני נמוכה בהשוואה לסביבה. לכן אזור זה מושך אליו הן יזמים סבלניים והן יזמים לא סבלניים. במקום מתרחשת פעילות בנייה נמרצת עד אשר החלקות בהן זמן אופייני נמוך אוזלות שוב. ברגע זה, יזמים סבלניים מתחילים לחפש הזדמנויות במקומות אחרים בשולי העיר. הדינאמיקה של ההתפתחות האורבאנית מתאפיינת אם כן במחזורים של פעילות בנייה מואצת, בהם המוקדים המשניים נוצרים, הבאים לאחר פרקי זמן של הפעילות מועטה בלבד. באמצעות מודל הסימולאציה ניתן למדוד ולנתח את המחזוריות של הדינאמיקה העירונית לאורך זמן.

לסיכום, המודלים המוצעים במחקר זה מתמודדים עם לידתה של עיר רב-מוקדית אידיאלית והדינאמיקה המאפיינת אותה.
במודלים אלו, הביקוש למיקום בעיר נמצא ברקע, אולם הדגש המרכזי הושם על ההתנהגות הנובעת מהיבטים של ההיצע. בפרט, הניתוח מתמקד בדרך קבלת ההחלטות של יזמי נדל"ן תחת אילוצי תכנון, ויחסי הגומלין בינם לבין קובעי המדיניות בעיר.
במודלים מסוימים, מוצגות השוואות בין מספר מצבים סופיים אליהם המערכת העירונית עשויה להגיע בהתאם להנחות מסוימות.
מודלים אחרים נבנו באמצעות כלים המדמים התנהגות של סוכנים. באמצעות אותם כלים ניתן לחקור מערכות עירוניות לאורך זמן, ולבחון את התהליכים המאפיינים אותם.

המחקר מוכיח שהאינטראקציות בין יזמים לבין רשויות התכנון יוצרות דינאמיקה עירונית רחוקה משווי משקל יציב. אחד המאפיינים של דינאמיקה עירונית זו הוא הופעתם הפתאומית של מרכזים עירוניים משניים. מאפיין נוסף של מודלים אלו הוא יצירתם של מחזורי התפתחות עירונית מואצים ורדומים לסירוגין. מאפיינים אלו של הדינאמיקה העירונית הנוצרת על ידי המודלים תואמים למנגנונים של Self Organizing Criticality (SOC). המחקר בוחן גם את המידה בה ניתן לסווג תהליכים אורבאניים, כמו אלו שמתקבלים באמצעות המודלים, כעונים על הקריטריונים של מנגנוני SOC.

Table Of Contents

1. Introduction

1.1. Motivation and research contribution

Visiting an unfamiliar city for the first time can be an instructive exercise for understanding the basic questions that shaped academic disciplines currently known as regional science, location theory and urban economics.

Approaching the city from the hinterland, it seems a priori that it should be easy to determine whether the traveler is outside the city or within it. Large parcels of cultivated land, open spaces or woods alongside the road may indicate that the city limits were still not reached. However, clusters of industrial facilities surrounded by open spaces or agricultural land could be an indication that the city boundary is near. A neighborhood, apparently isolated from the urban area that appears near the road may also indicate that the city is near. Gradually, the density of houses and constructions increases, and the route is transformed into an avenue, with houses, shops and offices. Public facilities, such as schools, fire stations and hospitals can be seen alongside. No doubt, the traveler is already inside the city, but a clear-cut boundary between urban areas and hinterland is very difficult to define.

Once within the city, the locations of destinations may differ according to the journey's objective. Tourists' areas, in addition to historical or architectural attractions, tend to be surrounded by services, such as hotels, restaurants, travel agencies, theaters etc. Sometimes this is the same area as the city's business center. Administrative facilities, such as the city's council and regional or national government offices may be located near these areas too. In many cities, it is quite clear where the urban core is. Any resident will be able to indicate how to get to the city center. Usually the center has a concentration of high rise buildings and a mix of several activities and services. However, as the traveler may discover from a casual walk around the city, sometimes the city's physical structure presents unexpected changes. Peripheral neighborhoods with low houses suddenly mutate on clusters of relatively high residential buildings, or shopping centers and commercial facilities are found at unexpected sites. Moreover, it is possibly that several urban centers exists, each one specialized in a specific activity type, such as tourism, business and shopping. In other cases these can be comprised of a mix of different activities, such as residential, business, administrative or commercial.

The questions stemming from an imaginary first visit to an unknown city are related to the main issues of economic geography: Why is the distribution of population on the landscape uneven? What is the force which attracts people to densely populated areas? How do cities emerge? Broadly speaking, these questions address the location of economic activities in space and the reasons for particular spatial arrangements. At a more local level, assuming the existence of agglomeration forces which justify the emergence of cities, other type of questions arise: Why do cities of different size exist? How do specific economic sectors (manufacturing, commerce, etc.) locate within a system of cities? Drilling down into the structure of a specific city, more specific questions could be addressed: Why a central business district (CBD) emerged in most of cities? Is the CBD the only place where all the urban economic activities are concentrated? Is the urban structure best defined as mono-centric or as poly-centric?

The disciplines previously mentioned (economic geography, regional science, location theory and urban economics) aim to study these and related questions. The conceptual framework of the present thesis is located on the intersection between a branch of regional science (gravity theory and the interaction of cities with different sizes) and urban economics. Its goal is to provide a set of urban economics models able to explain the emergence of poly-centric cities, based on the interaction between real estate entrepreneurs, urban development policies and a background of growing population. The models presented here are focused on the supply side. The physical structure of the city is the outcome of successive real estate developers' decisions, and those are influenced by the land use policies implemented in the city over time. In a universe of existing urban models driven mainly by the demand for dwellings and accessibility, supply focused models are an original contribution.

Some of the tools used for developing the models are well known in the field of urban economics. Such, for example, is comparative static's analysis. However, other instruments, such as agent-based models are relatively new. Using them makes it possible to illustrate dynamic urban processes that otherwise are intractable or at least very difficult to implement. This is a second novelty of this work. The explicit modeling of planning policies and their consequences when interacting with land developers is an additional contribution to the urban economics field. In particular, the models developed here demonstrate that this adversarial interaction is a main cause for structural changes in the urban structure, namely the transition from a mono-centric city to a poly-centric one. Finally, the dynamic approach implemented through the agent-based model allows analysis of the urban system not only as a social one, but to look at it as a physical system that responds consistently to "natural" laws, at least to a certain extent.

1.2. Mono-centric theories vs. empirical urban dynamics

Classical approach to the spatial structure of cities results in an ideal mono-centric urban structure (Alonso 1964, Mills 1967, Muth 1969). In these models, the exclusive driver of the formation of urban spatial structure is demand for proximity to city center (Glaeser 2008). The winners that gain proximity are willing and able to pay more than others. As a result, land rents at the central business center (CBD) are high and decline monotonically as distance from it increases. Assuming that location preferences and willingness to pay remain constant, as population grows the spatial structure of cities does not change, while the outer boundary expands. Just like a sand pile to which more and more sand grains are added at the top, the city's outer boundary moves out like a wave in all directions around the CBD.

Heretofore, empirical tests of the spatial structure implied by the classical urban model utilized crude tools and averaged data to estimate rent gradients and decreasing exponential functions (e. g., Alperovich, 2000). The observed empirical regularities are true at the crudest geographic resolution only. Even casual empiricism suggests that at a finer resolution the evidence is quite different (Anas et al. 1998). For example, analyses of high-rise buildings distribution and clustering over time in Tel Aviv suggest that urban spatial dynamics are discontinuous in space and non-uniform in time (Roth 2009; Golan 2009).

The growing acknowledgement that the structure of metropolitan areas bears little resemblance with the mono-centric structure expected by Alonso-type models gave birth to sub-center identification literature in urban economics (Giuliano & Small 1991). Theoretical predictions about employment sub-centers were assessed in a variety of urban areas (McMillen & Smith 2003). Empirical criteria and methods for the identification of employment sub-centers were subject of debate among scholars for long time (Griffith 1981, McDonald 1987, McMillen & McDonald 1997, McMillen 1998, McDonald & McMillen 2000, McMillen 2001). Empirical studies about spatial decentralization and urban sub-centers emergence are available too (Krakover & Adler 2007). Although several methodological questions in this field are still discussed (McMillen 2004), an important conclusion to be drawn from those works is that poly-centric urban structure is widespread.

Temporal patterns of urban building activities display uneven trends and give credence to the notion that urban spatial expansions display sudden bursts. At least in part this is due to the fact that construction activities are subject to periods of fast expansion followed by periods of slow growth. Some of the expansions are limited is size, while other are huge. This, and secular trends in real estate prices, suggest that supply tends to follow demand changes with lags and that cities tend to stay in situations out of equilibrium for relatively long times.

In cities in which population growth is stagnant and during periods of macroeconomic downturns low demand leads to lethargic behavior of developers. Some developers utilize such periods to purchase land parcels for future development, including land that is not zoned for those purposes. Periods of rapid population growth and economic expansions create high demand and consequent housing price bubbles (Glaeser et al, 2008). This is followed by fervent search by developers for all available, developable land parcels. Eventually, construction activity booms. It seems that there are local forces generating additional, more refined, cycles of fast growth followed by periods of slow growth. There is growing evidence that the speed of spatial expansions in some cities displays irregular patterns (Liu et al, 2010) and that the process occurs at very different rates in different zones of cities (Cao et al, 2011).

In conclusion, the physical evolution of the city is comprised of various interrelated processes. The time evolution of heights, their spatial spread, sub-centers emergence over time, sudden bursts in the overall development activity and uneven spatial expansion of the urban area. All these processes do not accord well with the Alonso-Mills-Muth framework.

1.3. Urban dynamics factors

The task of municipality planning authorities is to regulate the land use within the city boundaries. In areas where clear zoning restrictions exist, strict regulations are implemented prohibiting certain development projects. In less restricted areas, this task is performed by allowing quick approval of building permits that are consistent with the planning directives. Conversely, land use change requests and building permits that do not conform to land-use plans, the so-called variances, are delayed. From the point of view of real estate entrepreneur's, these time delays represent the period of time from the acquisition of initial property rights in land until the first return on the investment is realized. Borrowing a concept from physics, this time is called "characteristic time". Based on this concept, the appearance of high-rise buildings far from the CBD as a consequence of rational choice of profit-seeking developers can be explained (Czamanski & Roth, 2011). This result is different from outcomes derived by Alonso-Mills-Muth model types. Thus, a first possible factor for the emergence of sub-centers is the choice of a profit-seeking developer under particular conditions created by planning authorities.

The characteristic time function is the outcome of regulatory processes and reflects urban development policies. Consequently, the behavior of the municipality planning boards over time is another important factor to be considered when analyzing the emergence of sub-centers. This is evident in cases when the authorities, for various reasons, promote the spreading of development by encouraging real estate entrepreneurs to search for opportunities far from the city core. Such is the case when there is lack of sufficient infrastructure to support urban growth in the CBD. But more subtle situations in which urban policies are involved may exist .

For example, in the case of two neighboring cities competing or collaborating planning policies can arise. Depending on the physical location of the administrative boundary between the jurisdictions, the policies implemented by one may encourage the emergence a new sub-center near the second, either purposefully or unintentionally. The spatial configuration of two neighboring cities and their jurisdictions may lead to several development scenarios. These can be further elaborated assuming that both cities are qualitatively and quantitatively different in terms of urban amenities, employment opportunities and population size. In such case, the attraction exerted by both cities in a particular place, will be different. These gravity forces are expressed by the willingness to pay for dwellings at various locations. The combined influence of the cities' policies, territorial jurisdiction and socio-economic attraction offers plenty of reasonable scenarios for the emergence of urban sub-centers.

Furthermore, as conditions in the city change, developers' choices and municipality's policies may change over time, as well. The reciprocal relationship between developers and planning authorities can be hypothesized as a third important factor behind the city spatial-temporal evolution. Both parties (the city and the developers) may create new situations dynamically, causing the other to modify its behavior. For example, large periods during which land development activities are constrained may cause real estate entrepreneurs to embark into more capital-intensive projects, or to build concentrated clusters of buildings at the urban fringe, despite city's regulations. This in turn may cause planning policies changes, at least in certain areas .

Moreover, should different types of developers be introduced, differentiated by their financial strength, size of their operations or their risk aversion, a wider range of possibilities can be explored. Various groups of developers can react differently to a change in the city configuration or as a response to a political turn .

To sum up, the supply side of the urban market and its mutual relationship to city policies and regulations, subject to different spatial and temporal configurations, is a fruitful field for understanding urban dynamics and, in particular, the emergence of urban sub-centers.

1.4. Theory, models and economics

Virtually all economics textbooks include frequent references to models, used to illustrate some aspect of the theory being developed. Since the same is true here, it is worthwhile to define the meaning of models in the context of the economic theory in general, and addressing the dynamic emergence of urban sub-centers in particular.

First, it is important to note that the relationships between the concepts "model" and "theory" are different according to the disciplinary framework. For example, mathematical logicians tend to understand a model as representing logical rules (not necessarily meaningful) that underlie a theory. The theory itself is in this case a meaningful specific interpretation of the logic embedded in the model. In engineering, a model is often understood as a specific case of a broader theory being studied. These are opposite interpretations of the relation between the terms (Boland, 2000). In economics, a model is a simplified description of the reality, specifically designed to test hypotheses about the economic phenomena under study. In other words, an economic model is intended to describe an ex-ante economic theory. It is important to emphasize that both terms are not interchangeable in economics. "Theory" is the pre-existing framework of ideas. However, a model is neither necessary nor sufficient for theory creation (Klein & Romero, 2007).

Klein and Romero (2007) developed an assessment method for models which can be considered to qualify as theory. The method is based on three evaluation queries about the model in question. In what follows, these three queries are applied to the set of urban economic models developed here, in order to demonstrate that according to this test, they constitute a genuine contribution to the urban economics scientific literature.

"*Theory of what?"*. In order to answer this question, the modeler should indicate the real world phenomena which gave the motivation for the model, and convince that the model helps explain the phenomena. In this case the real-world motivation is the ubiquitous presence of poly-centric cities. The set of models are able to describe the mechanism underlying sub-center emergence in cities in a reliably and convincing manner .

"*Why should we care?".* The proposed model should de adequate for the explanation of the phenomena and merits the scientific community attention. In this case, urban dynamics and poly-centricity are being extensively studied in the last years, both under theoretical and empirical approaches. The models proposed here stand at the core research issues of several branches of urban economics and regional science .

What merit in your explanation?". Although there were previous efforts to explain sub-centers emergence in the context of urban economics, both the supply side approach implemented, and the analytical and simulation tools used here are novel and original in this field.

2. Existing knowledge

2.1. Urban economic models

In the early XIX century, Von Thünen (1826) developed his classic model of joint determination of agricultural land use and land rent. He assumed an idealized isolated state composed by a very large town in the center of a fertile plain surrounded by an agricultural hinterland. In his model, although the soil is equally fertile everywhere, different crops differ both in their yields per land unit and their transportation costs. The land is assumed to be owned by absent landlords and is bided to farmers. The only marketplace is sited in the unique central town and therefore each self-interested farmer seeks to minimize its production and transportation to the market costs. Since freight requirements and yield differ among crops, there is a tradeoff between transportation costs and land rents. A farmer growing crops which are expensive to transport prefers a parcel as close as possible from the central town. With the transport costs savings he is able to pay a higher land rent nearer the town. This tradeoff is the cause of the appearance of a pattern of agricultural production concentric rings. Von Thünen showed that competition among farmers and landowners leads to a gradient of land rents that declines from a maximum at the central town to zero at the outermost limit of cultivation. Moreover, he showed that the unplanned competition outcome minimizes the combined production and transport costs of the food supply to the town .

In that sense, Von Thünen has created one of the first models of economic general equilibrium (Samuelson 1952 cited by Fujita 2010). This early agricultural model may seem simple, but it highlights some not obvious features. The emergence of spontaneous optimal order from the uncoordinated effort of several types of agents is one of them. From the point of view of a social planner, the land allocation problem in the isolated state is not a simple one. If a crop type is cultivated in a specific plot of land, it affects indirectly the allocation of all others, because they need to be cultivated anywhere else. This in turn affects the delivery costs of all the agricultural supply. The unplanned spatial configuration resulting from competition is an optimal solution of the social planner problem.

Urban economics, and in particular modern land use theory, is in essence a generalization of Thünen's concept of bid rent to an urban context. Alonso (1964) developed the mono-centric city model, in which the central business district (CBD) takes the central town role of Thünen's model. The surrounding land is residential, instead of agricultural. All production activities are assumed to take place at the CBD, with workers commuting to work from the residential area around it. The combined agricultural transportation and land rent costs were transformed into combined commuting and urban land rent costs, instead. However, Alonso developed its model a step further. In the naïve Thünen's model, all farmers were assumed to be identical. This implies that as long as total revenue exceeds total cost, they are indifferent among all locations. If farmers are allowed to be different, they can engage in factor substitution. Increasing non-land inputs, as labor and equipment, they are able to locate on more central and expensive parcels. As a consequence, the bid-rent function becomes convex. This means that at central locations land is used more intensively and, hence, more efficiently. Far away for the central town, non-land inputs are fewer and, since the land is cheaper, it is used more extensively. Still, the basic feature of the model remains unchanged and at each location rents equals the profits of the highest bidder.

Back to Alonso's urban implementation, different firms, engaged in different production activities perceive land-rents as a production factor with variable substitution rates. For example, office firms which require physical and daily access to services like lawyers, consultants and accountants value central locations more than industrial firms. Additionally, office firms usually require face-to-face accessibility. If the pay rate of skilled office workers is very high, they "unproductive" travel cost is high either. This reason enforces the importance of central locations for this type of firms. Therefore, their bid rent function is steeper than the bid rent of other activities, and it is expected that they will occupy the most central land. Although all firms are attracted to the CBD, only those, as offices, which are willing to bid enough locate there. The office firms have the most to gain from being in the CBD. Industrial firms could gain too, but less than their counterpart, and therefore they locate further away. In this sense the market allocation in this model is efficient.

The same logic applies to dwelling choices. If commuting costs are low relative to freight transportation costs, manufacturing firms bid more than residential uses, and workers are pushed to live in the urban periphery. In other words, residents are attracted towards the center but are outbid by offices and manufacturing.

Within the residential market, a similar analysis holds. Dwellers engage in consumption factor substitution, consuming less land as its price increases, and consuming more urban amenities instead. This fact explains why houses in central places tend to be smaller than houses in the city's periphery. Consumer substitution and production factors substitution can explain why urban density increases towards the CBD. As price land increases near the center, they response using less land per unit of housing or production, increasing land use density.

Alonso's model provided a sound theoretical foundation to the field of urban economics. The model was extended by Mills (1967) and Muth (1969) incorporating resources allocation within the urban area and a detailed analysis of the residential market into the model, respectively. The Alonso-Mills-Muth model became the most significant framework in the field of urban economic theory to date. As it agricultural model predecessor, it is based on the notion of spatial economic equilibrium. Individuals, workers and real estate developers, are assumed to be willing to trade space for locations within the urban area. This result is explained by Glaeser

(2008) noting that in equilibrium each of the urban agents should be indifferent across space. For individuals, wages plus amenities minus housing costs should be constant. But firms should be indifferent across space too. This means that wage differences must be offset by different productivities for employers. In the case of real estate developers the consequence of the indifference assumption is that housing prices should be roughly equal to the sum of construction costs, land price and regulation costs everywhere over the urban landscape.

Although the mono-centric Alonso-Mills-Muth model has proven to be an extremely useful framework for studying urban economics problems, it has drawbacks. The most obvious one is the assumption of the a-priori existence of the CBD. This issue has been addressed by a branch of the New Economic Geography (NEG) that deals with urban systems. For example, a linear world model populated by mobile workers and immobile agricultural land developed by Fujita and Krugman (1995). The model starts with a Thünen-type city surrounded by agricultural land, and is used to obtained agricultural-manufacturing equilibrium conditions. If the population gradually increases, as simulated by Fujita et al (1997), the hinterland grows and at a certain time it becomes worthwhile for some firms to move away, giving rise to a new city.

There is another branch of urban economics which deals with urban systems. The basic idea behind this model is that within a city there is always tension between centrifugal and centripetal forces. The centrifugal forces are the agglomeration externalities, and the centripetal are diseconomies of size, as noise, pollution and commuting costs. Therefore the relationship between the city dweller utility and the city size take a form of an inverted parabola (Henderson, 1974). Agglomeration benefits are specific for each industry, but agglomeration diseconomies depends on the city size, regardless what it is produced. Therefore, different specialized cities with various urban sizes are expected to coexist.

Another drawback of the Alonso-Mills-Muth model stems from its prediction that cities have only one dominant center. Most modern cities can hardly be described as such. Sprawl is a widespread urban phenomenon. Scattered spatial development and the emergence of sub-centers are difficult to explain within this framework. However, there have been efforts to fill this gap in knowledge. There are studies concerned with the formation of sub-centers de novo (Fujita, 1982 and Fujita et al 1997, Helsley & Sullivan 1991, Berliant & Wang 2008). Fujita bases his model on perfect foresight of developers. In a similar manner, Henderson and Mitra (1996) assume a single monopolist. Mills (1981) presents an economic model of landowner's decisions in a mono-centric city during two different periods, assuming that the economy is growing. Decision-makers' inter-temporal planning with certainty, can lead to leapfrogging if a fraction of the landowners preserve undeveloped land for future more remunerative options. In other words, developers speculate concerning future direction of urban development and thus anticipate the future in their decisions. Wheaton (1982) develops a model in which landowners with perfect foresight maximize their inter-temporal present value of land rent. In particular, he shows that leapfrogging can arise under specific ranges of model parameters that cause development from outside in. Fujita (1982) uses similar assumptions and demonstrates that, regarding residential dynamics, perfect foresight results in increasing population density in certain areas far from the CBD. Following Fujita's (1982) model, Turnbull (1988) investigates the residential development process in an open city. His results do not necessarily resemble previous models, as interior areas which remain undeveloped, and development direction does not always proceed from the CBD outwards.

The third drawback of the Alonso-Mills-Muth model is its innate static nature. As Glaeser (2008) points out, the behavior of individuals, as employees and consumers, and companies, as employers, producers and dwellings providers, is modeled within an idealized general equilibrium framework. This equilibrium framework leads to an explanation of the urban spatial structure. Even later models of urban development based on the same premises, but aimed to explain more complex issues such as sprawl and sub-centers are built as series of different equilibrium outcomes, resembling stills photographs that depict a series of not-fully connected static situations.

In the economic literature there are efforts to model and analyze out of equilibrium situations. Although related mainly to macro-economic problems, a wide range of econometric methods capable to cope with disequilibrium frameworks were developed (Fair & Jaffee 1972, Maddala & Nelson 1974). Following these seminal works, more recent efforts in fields as micro-economics (Bode et al 1998) and macro-economic dynamics (Franke 2001, Benetti et al 2007) were performed. Closely related with urban economics issues, a model addressed to estimate disequilibrium in regional interactions using spatial econometrics is available (Snell 1999). Housing markets disequilibrium dynamics were assessed empirically in the last years in a wide range of test-cases (Riddel 2004, Jang et al 2010, Lee et al 2011, Chen et al 2011). Although none of these models was applied to problems similar to those discussed in this thesis, they offer clues about how econometric tools could be used in the field of empirical out of equilibrium urban economics.

It is noteworthy that the Alonso-Mills-Muth model focused on the demand side of the market only. The vast majority of the various elaborations and applications ignored the supply side, the considerations of planners and developers and the characteristics of locations (examples of some exceptions are Henderson et al 1996 and Benguigui et al 2008). The classical models assume homogeneity of consumers and of producers except for one parameter – the consumers' willingness to pay for proximity to the urban center. Furthermore, political and administrative issues are also absent from the classical model framework. Different types of urban policies implemented at different times and addressing a wide array of issues should influence heavily the pattern of urban and metropolitan development. The Alonso-Mills-Muth model does not take into account these factors.

2.2. Regional economic models

A crucial aspect remains unanswered in Thünen's model. All manufactured goods are assumed to be supplied from the town, but the forces that attract manufacturing activity to it are ignored. Location theories including Marshall's study of industrial agglomeration (1890) and Weber's theory of industrial location (1909) offer clues to understand this question. Marshall searched for the reasons that lead industries to locate and concentrate in certain locations. He claims that production externalities are important in the formation of economical agglomerations. The first step can be assumed to be a casual location an industry in a certain place. Skilled people are attracted by the industry since they benefit from specialized work demand. Later other people are attracted by the larger array of activities created in the area and by the growing degree of specialization. This mechanism acts as a self-reinforcement machine in which both industries and workers increasingly benefits from the economic agglomeration. However, this model does not provide the micro-economic foundations behind what has been called "Marshallian externalities". In that sense it is more a description than a rigorous economical model.

In contrast, Weber's theory studies the optimal location for a hypothetical manufacturing plant. The localization of the production inputs and the output market is considered fixed, and the objective function is to minimize the total transportation cost per unit of output. Later, a situation in which labor costs varies with the location was contemplated. The work of Weber can be considered a pioneering theory of industrial location (Fujita, 2010).

An additional school of thought which deals with spatial economy is the central places theory developed by Christaller (1933) and Lösch (1940). The model assumes an evenly spread population of agricultural workers. Each farmer works on its land plot, but need several services. Those services are activities subject to economy of scale, as manufacturing (agricultural machinery, fertilizers, etc.) and administration (government services, education, etc.). The trade-off between transport costs and economies of scale leads to the emergence of central places which serves the surrounding farmers. Christaller showed that the central places form a hierarchy of increasingly complex and larger service areas. Similarly Lösch developed a model of firms producing a homogenous product in a framework of fixed consumers' locations that leads to the formation of hexagonal market areas. A similar story can be applied to the urban arena, for example assuming a nested hierarchy of shopping districts with great and specialized shopping centers in the highest levels, and small neighborhood shops in the lower hierarchy (Fujita et al, 1999).

2.3. Agent-based and cellular automata models

An alternative approach to equilibrium-oriented economic models comes from spatial analyses in other disciplines. Cellular automaton models are characterized by a small number of rules of behavior that are applied to spatial units called cells. At the start of the process all the cells are homogeneous. The rules are applied at the cell level and among many entities, namely, groups of adjacent cells. They create complex global phenomena, in the sense that the actions of the individual parts do not simply sum to the whole activity. Important system characteristic and behaviors are not observable by dissection because the system's richness lies in the collective outcome of the interactions of its elements. In this sense, this type of systems is defined as self-organizing and emergent (Holland 1998).

The concept of Cellular Automata (CA) was defined originally as a one or two dimensional grid of identical automata cells. Each automata cell process information, and acts according to data received by the environment and following its own internal rules. A set of states and a set of transition rules are enough to define the automata cells. When the set of inputs is defined by the states of neighboring cells, the whole grid becomes a CA (von Neumann 1951). The basic CA feature which links the transition rules of a certain cell to the current configuration of its neighbors fit well into one of the most famous statements in geography. According to Tobler's First Law "Everything is related to everything else, but near things are more related than far things (Tobler 1970)..

CA models have become dominant in the analysis of urban land use and development over time. Urban space can be conceptualized as a spatial coverage of many relatively small land units, each one with its own properties. Such conceptualization enables the study of urban land-use dynamics as CA simulations (Tobler 1979). The most popular application of the CA to modeling urban dynamics started with the constrained CA model of land-use dynamics (White et al 1993). This model assumed that the potential of a land cell to undergo a certain land-use transformation depends on the states of a circle of adjacent cells. The cell's possible transitions were defined as strictly irreversible (undeveloped state first, then residential, industrial use as a third stage and lastly commercial use). The basic goal was to reproduce realistic urban land-use patterns. Indeed, several real-world city dynamics were simulated successfully (White et al 1993, 1997). The introduction of additional urban infrastructures as roads, railways and water bodies as additional urban development constraints lead to more successful urban evolution simulations (Xie, 1996; Batty and Xie, 1997, Semboloni, 2000). CA models are widely used to simulate real-world urban dynamics, but their transition rules settings are well defined but not always satisfactorily justified, and some are overcomplicated (Benenson et al 2004).

Although a single cell in a CA grid has some characteristics attributable to an agent, it lacks other important characteristics. An autonomous agent can be defined as an entity within a given environment, able to sense and act on it over time pursuing its own agenda (Franklin et al 1996). Following that definition, a CA model can not satisfy the last condition. In order to enhance the analytical power of any urban model, human behavior and goals should be incorporated as an inevitable part or them. Urban CA models resemble arrangements of physical particles (parcels, houses, etc.) that evolve following external laws (Weidlich 2000). However, "the will" of the house or parcel owner is ignored. Conceptually, the agent-based framework embedded in CA models is necessary when individual decision-making influence the change of a system element state. Two distinguished principles can be defined for agents in urban environments. The first is spatial location and spatial relationships. The second is the adaptability to a changing environment (Benenson et al 2004). Both principles are hard to implement in static simple CA models.

Agent-base models were applied widely to study urban phenomena. Residential dynamics of households, based on their cultural identity and economic status, were used to study the city's cultural self-organization (Benenson 1998). Ethnic characteristics and social preferences were implemented using a modified Schelling model (Schelling 1969). The model allows a detailed reconstruction of several cities residential dynamics (Benenson et al 2009). Future land uses and residential trends expected at local and regional levels can be modeled through life cycle stages of the population. Changing family configurations and dwelling preferences over time are the main driver of this type of models (Fontaine et al 2009).

But it is in the field of land-use dynamics that agent-based models combined with cellular automata settings are most actively applied. According to an extensive report on agent-based models of land-use change, the discipline is mature enough to be characterized (Parker & Berger 2001). Models must be spatially explicit, incorporating agents which make decisions based on a cellular representation of the landscape. Distance-dependent spatial interactions are particularly relevant. Social-environment interactions should be included linking the agents decision making with environmental processes. Also, they should reflect human behavior heterogeneity representing multiple agent types in the model. If a model is implemented in order to examine exogenous factors impacts, as policy modifications, urban-rural dynamics or technological innovations, there is an additional requirement. It must be able to analyze comprehensively the system response to these exogenous influences. Only fulfilling this requirement a model can be used as a tool for policy analysis. Finally, the ability to identify cross-scale representations, both at the spatial and the temporal level is an important challenge for this type of models, due to its complexity (Parker & Berger 2001).

Rural land use change models include farmers' characteristics and decision making strategies within different institutional frameworks. These are valuable tools for evaluating agricultural policy outcomes at a regional level (Valbuena et al 2010). A similar combination of multi-agent simulation with cellular automata was proven as a valuable tool for spatial planning

(Ligtenberg et al 2001) and assessment of rural sustainable development (Wu 1998). The land use dynamics in the interface zone between the urban and the rural systems were studied and simulated using a plethora of combined theoretical and empirical tools (Irwin et al 1998, Irwin et al 2002, Liu et al 2003).

A comprehensive review of the state of the art in the field of economics models of land use change and possible new research directions was published recently (Irwin 2010). The review proposes a structured framework for agent-based models in that field. The goals of such modeling are twofold. First, to identify underlying processes that explains observed spatial patterns. The second goal is to understand the processes' influence on the system dynamics over time. A good model should be able to answer questions about the following issues. What are the empirical regularities of the time-spatial dynamics at the macro level? What are the micro foundations that explain them? And lastly, what are the system-level dynamics which emerge from those micro foundations? (Irwin 2010).

Within the economics agent-based models, CHALMS (Coupled Housing and Land Markets) deserves a particular mention. The model simulates the conversion of farmland to housing over time through the bidding actions of agents in the housing and land markets (Magliocca et al 2011) and is able to simulate representative suburban areas growth. Although CHALMS is able to capture general sprawl processes better than previous models, it is quite complex and involve large sequences of interacting sub-modules.

Most models of this type do not incorporate traditional economic agents in the simulations. A recent three dimensional simulation model of cities, including building height information, was able to simulate several typologies of urban development patterns and included economic agents (Benguigui et al 2008). A potential development function and a small set of parameters with simple economic interpretation were used. Different fundamental city types results from the dynamic processes created by the model.

3. Research Methods

Equilibrium oriented classical models of urban spatial structure are hard pressed to explain the formation of modern cities with polycentric structure and the births of sub-centers in particular. On the other hand, existing cellular automata and agent based models are able to explain land use dynamics in a wide spectrum of situations. The third spatial dimension, which is of paramount importance in cities, is almost always neglected. In the following, new models were developed for analyzing the type of situations and dynamics that characterize poly-centric urban evolution are described.

3.1. Comparative statics analysis – Single developer

The spatial distribution of height of buildings may be discontinuous on space. Sometimes, high rise buildings appear in peripheral areas, and not necessarily near the CBD (Roth 2009). The interesting question in these cases is the cause for a rational, profit-maximizing developer to choose to build a new high rise building far from the existing CBD. A linear space model that uses the concept of characteristic time and a comparative static's approach demonstrates that under certain conditions a profit-maximizing developer will prefer a distant location for his enterprise rather than near the CBD. This result was interpreted as a possible cause for the emergence of urban sprawl (Czamanski and Roth 2011).

Following that model, in which the presence of a single municipal authority and a set of stable rules determined the spatial incidence of characteristic time, the analysis can be extended to the case of two cities. In this case the spatial incidence of characteristic time is determined by a municipality within its own boundary, independently of its neighbors. The characteristic time in each authority is an outcome of the behavior of several interacting actors and agendas, including the municipality's planning authorities, neighbors' idiosyncrasies, NGOs' agenda and others. In other words, each planning authority reflects the preferences of its self-selected residents. Two different policy assumptions can be analyzed. Myopic behavior means that each actor (planners, NGO's, citizens) acts as if what happens beyond his municipal boundary is not of his concern. Relaxing the myopic behavior assumption, all actors in both municipalities are aware of the prevailing characteristic time throughout the entire linear segment, and act in consequence.

The central question is the location decision of a hypothetical real estate developer searching for the next parcel suitable for development. The function of a real estate developer is to convert land from lower to higher use, increase its value and profit from these actions. Therefore, its choice will be heavily influenced by the characteristic time imposed by the authorities in their respective territories. Assuming similar or different development policies in each one of the municipalities, several developer's choices arises, some of them consistent with compact city development, and some of them causing scattered urban development.

The tool used within the context of the model is a profit function that the developer maximizes. The profit depends on the land costs, the dwellers' willingness to pay and the characteristic time at any given location. In this sense, the results are an outcome of a comparative static's analysis of the developer's best choice under each of the scenarios checked. The full model is described in the paper "Developers' choices under varying characteristic time and competition among municipalities", included in the "Findings" chapter.

In that initial model, both cities were assumed to be similar, since the research question was focused on the effect of the characteristic time function and the jurisdiction boundary on the developer's best choice. The situation changes if the cities are assumed to be qualitatively different, in terms of population, size, purchase power, etc. One is a developed city, with high population, of at least one order of magnitude greater than the other. Consequently it offers diverse urban amenities as employment, manufacturing and business as well as consumer facilities and educational options. The second one is assumed to be a small city, much less populated than the first one and with a narrow spectrum of urban services, but offering country-side amenities as open spaces, less agglomeration, etc.. Furthermore, it is assumed that both are located at a commuting distance, meaning that it is possible to live in the small city and work and/or consume cultural products at the big one.

From a consumer's point of view, the willingness to pay for a house in this linear model is mainly a function of the distance from the main central business district, as assumed by the mono-centric urban models (Alonso, 1964; Mills, 1967; Muth, 1969; Wheaton, 1982). Since the linear space is bounded by two business districts, each exerts an attraction that operates along the entire segment. The strongest attraction forces operate on the edges themselves, being much more powerful in relation to the CBD of the bigger city. Along the segment they are expected to decrease as the distance from the biggest city is increasing (Osland & Thorsen, 2005; Osland, 2008). Smaller city's attraction force causes it to rise eventually as the proximity to its CBD increases. The willingness to pay for housing is assumed to be the emerging result of those gravity forces.

The main idea is a focus on the necessary and sufficient conditions needed to generate building activity away from the center and from the last built parcel on the horizontal axis. The interesting aspects of urban dynamics are associated with the absence of equilibrium. Developers purchase land at low prices and before others have moved in to increase land price to a new equilibrium level. The question that is addressed is how the actions of planners affect the creation of local maxima in profits and thus generate building activities and the formation of new sub-centers. Once a local maxima are created the dynamics of developers leads to a new equilibrium.

Since both cities are qualitatively different, additional forces and interactions between them emerge. In this scenario, mutual attraction forces will operate along the entire region, interacting with the political boundary between them, which not necessarily reflects the gravity influences shaped by the market forces

If each city behaves myopically, interested only in what happens on its side of the boundary, leapfrogging patterns can easily develop. Even full awareness, in the sense that each city takes into consideration processes in the entire region, can result in intentional leapfrogging created by competition between the cities. However, in this case, spatially concentrated development is possible, depending on the policy objectives of the authorities. Additional scenarios of collaboration between authorities with different goals are also feasible.

The model simulates processes occurring during a phase when both cities are growing, and the land and residential markets are not in equilibrium. In the long run an equilibrium stage where profitability is the same everywhere will eventually be reached, but our interest is focused on the long period (years or decades) in between. In such disequilibrium situations, local maxima in profitability are possible, for example in some of the scenarios depicted before. Those local maxima can be intentionally or unintentionally created by cities authorities, emerging from non-monotonic time incidences on development along their territories. Since profitability is highly influenced by time incidence, developer's location decisions can be very different from results expected by models assuming monotonic profitability decline from the CBD.

In the final stage of the evolution (the equilibrium stage) assuming a steady population growth, the model will yield an urban continuum in which the small town becomes part of the big city. However, the main question addressed by the paper is how the spatial configuration will change during the long time between the initial setting and the equilibrium stage. In order to simplify the model settings it is assumed that developers are willing to erect only fixed-height buildings. The question becomes which zones within the linear space will be developed first, and in which order. In other words, the model seeks to depict the regional urbanization dynamics. The full model is described in the paper "Cities in competition, characteristic time and leapfrogging developers", included in the "Findings" chapter.

3.2. Economic analysis with multiple developers

As long as cities planning policies can be modeled in terms of the spatial characteristic time which impacts directly on the objective function of a single developer, representing an idealized average developer behavior, comparative static's methods are relatively simply and productive. However, if the regulation authorities need to adopt a dynamic behavior and the developers will be assumed as a heterogeneous group of agents with differentiated goals, simple comparative static's methods become complicated and less tractable. Moreover, since a dynamic approach is required, the behavior of all involved agents and economic parameters need to be able to change over time. As a result, a dynamic economic model which includes both demand and supply of dwelling in a spatial context is required for such qualitative improvements.

The main drive of the model is the profit objective function of real-state entrepreneurs, as defined previously. There are two types of real estate developers. The first type is an impatient developer, characterized by small scale operations resulting in low and medium height buildings and preference for immediate returns on investment, henceforth "small" developers. The second type is patient developer, characterized by financial capabilities, ability to wait long periods in order to maximize returns on investment and large scale of development operations (high rise buildings), henceforth "big" developers. Assuming that N “small” developers and M "big" developers are present, the following objective functions hold:

$$\begin{aligned} &MaxFV_{x,h,q}(t=\tau) = -I_q(x)\cdot(1+r)^{\tau} - C(h) + WTP_q(x)h \\ &s.t.\tau = \tau(x,h) \end{aligned} \quad (1)$$

$$\begin{aligned} &MaxFV_{x,h,q}(t=\tau) = -I_q(x)\cdot(1+r)^{\tau} - C(h) + WTP_q(x)h \\ &s.t.\tau = \tau(x,h) \wedge (\tau < T) \end{aligned} \quad (2)$$

Symbol	Meaning	Symbol	Meaning
FV	Future value	I	Investment (land cost)
q	Current time	r	Interest rate
x	Location	C	Construction cost
h	Height	WTP	Willingness to pay
τ	Characteristic time	T	Maximal waiting time

Where $I_q(x)$ represents the land price as a function of location x, r is the discount rate, $C(h)$ is the overnight building cost is a function of building height and $WTP_q(x)$ is the willingness to pay of buyers at location x. The q index symbolizes the time at which those future values are calculated. Both $I_q(x)$ and $WTP_q(x)$ changes by time as the market parameters evolve. The objective functions for "big" developers (equation 1) and "small" ones (equation 2) are the same excepting for their waiting time aversion. In the "big" developer case (henceforth "patient" developers) there is no constraint for the waiting time τ. "Small" developers (henceforth "impatient") future profits are subject to an additional condition: The waiting time τ must be lower than their maximal willingness to wait, T.

Building costs are defined as an increasing cost function as building heights rise. They are given by

$$C(h) = c_1 \cdot h^2 + c_2 \cdot h + c_3 \qquad (3)$$

Symbol	Meaning	Symbol	Meaning
C	Construction cost	c_1	Parameter (positive)
h	Height	c_2	Parameter (positive)
		c_3	Parameter (positive)

Where c_1, c_2 and c_3 are positive parameters.

The model's spatial playground is a square grid of cells with size $K \times K$. Each cell represents a land parcel available for urban development. Initially, only one parcel is occupied, representing the original city's CBD. The cells' status in any given time step is characterized by several attributes:

- Characteristic time: The time delay imposed on each specific cell by city authorities on potential developers from the time that property rights are purchased and until the project construction and revenue realizations. This attribute is a function of location. Also, characteristic time increases with height.

- Cell use status: One of the following three statuses is possible – Available (not developed), purchased (waiting for the characteristic time elapsing, and therefore, not developed yet) or developed (an occupied cell with a building standing in it). Status can change over time.

- Height: Zero if non-built, otherwise the height of the constructed building.

Land price and willingness to pay for dwelling in each other parcel are function of two parameters: A base value which depends on the dwelling market demand and supply, and a location value which depends on the parcel emplacement with relation to all other already developed parcels. Both values are calculated for every time q.

$$I_q(x) = I_q^b + I_q^l(x) \quad (4)$$

$$WTP_q(x) = WTP_q^b + WTP_q^l(x) \quad (5)$$

Symbol	Meaning	Symbol	Meaning
I	Investment (land cost)	q	Current time
WTP	Willingness to pay	b	Base cost or price – Market dependent
x	Location	l	Location dependent cost or price

Where b stands for "base" and l stands for "location". In the following D_q represents the overall demand for dwelling in the market and S_q is the total supply (all the existing dwelling units regardless of their location). Both are calculated at each time q.

The "base" land values and dwelling prices fluctuate according to the demand / supply ratio at each given time. Their values reflect the overall dwelling market status, and they are not related to specific locations. For convenience, a linear equation was defined for the base values, allowing minimal and maximal value definitions:

If $D_q \geq S_q$

$$\begin{aligned} I_{q+1}^b &= I_q^b + \left(\left(I_{\max} - I_{\min}\right)/100\right) \\ WTP_{q+1}^b &= WTP_q^b + \left(\left(WTP_{\max} - WTP_{\min}\right)/100\right) \end{aligned} \quad (6)$$

If $D_q < S_q$

$$\begin{aligned} I_{q+1}^b &= I_q^b - \left(\left(I_{\max} - I_{\min}\right)/100\right) \\ WTP_{q+1}^b &= WTP_q^b - \left(\left(WTP_{\max} - WTP_{\min}\right)/100\right) \end{aligned} \quad (7)$$

Symbol	Meaning	Symbol	Meaning
D_q	Demand at time q	WTP_q^b	Market dependent dwelling price (basis) at time q
S_q	Supply at time q	$I_{\max,\min}$	Maximal and minimal allowable basic land cost
I_q^b	Market dependent land cost (basis) at time q	$WTP_{\max,\min}$	Maximal and minimal allowable basic dwelling price

The location value is based on gravidity calculations. It is assumed that a developed parcel exerts an attraction on its surrounding which is function of its height, decreases exponentially and is expressed by an additional willingness to pay. A building of height h at a parcel i causes on a neighbor parcel j a willingness to pay

$$WTP_{j,i} = \frac{WTP_b \cdot h_i}{d_{ij}^{\alpha}} \qquad (8)$$

Symbol	Meaning	Symbol	Meaning
$WTP_{j,i}$	Influence of parcel i in the willingness to pay on parcel j	h_i	Height of a building sited on parcel i
WTP_b	Market dependent dwelling price (basis)	d_{ij}	Distance between parcels i and j
		α	Attraction exponent

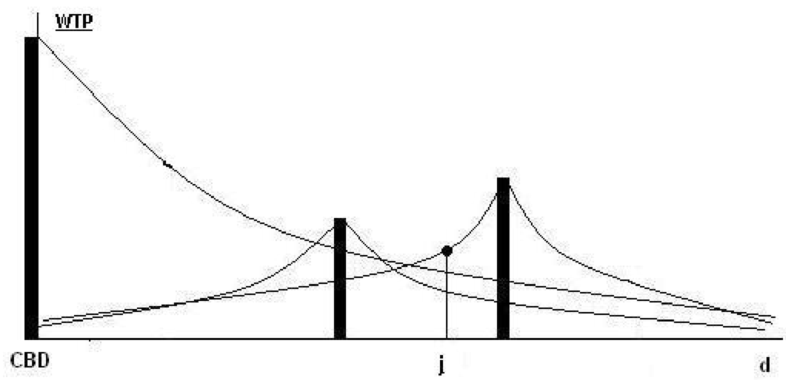
Where WTP_b is the basic willingness to pay for dwelling (not dependent on location), d_{ij} is the distance between i and j, and α is an attraction exponent. The previous equation does not include the time index (q) for the sake of simplicity. However, $WTP_{j,i}$ is calculated for each parcel j at each time q.

The location willingness to pay value for each available parcel is defined as the maximal influence exerted by all parcel's neighbors.

$$WTP_q^l(j) = Max\{\frac{WTP_b \cdot h_i}{d_{ij}^{\alpha}} \mid \forall i \neq j\} \qquad (9)$$

Symbol	Meaning	Symbol	Meaning
$WTP_q^l(j)$	Location willingness to pay on parcel j at time q	h_i	Height of a building sited on parcel i
$WTP_{j,i}$	Influence of parcel i in the willingness to pay on parcel j	d_{ij}	Distance between parcels i and j
WTP_b	Market dependent dwelling price (basis)	α	Attraction exponent

The following picture exemplifies the influence of three parcels on the willingness to pay in a fourth one, called j. For convenience all them are sited in a straight line, and the resulting $WTP_q^l(j)$ is marked.



In the same manner, the location land price on an available parcel is

$$I_q^l(j) = Max\{\frac{I_b \cdot h_i}{d_{ij}^{\beta}} \mid \forall i \neq j\} \quad (10)$$

Symbol	Meaning	Symbol	Meaning
$I_q^l(j)$	Location land cost on parcel j at time q	h_i	Height of a building sited on parcel i
I_b	Market dependent land cost (basis)	d_{ij}	Distance between parcels i and j
		β	Attraction exponent

Where I_b represents a fixed land value and β is an additional attraction exponent. Both values, $WTP_q^l(j)$ and $I_q^l(j)$, are calculated dynamically at each time q. It is assumed that $\beta > \alpha$, meaning that the willingness to pay decays slowly than the land price value.

The demand D_q is driven by the population growth, assumed to be linear. If P_q is the city's population at time q and ΔP is the linear growth rate, then

$$P_{q+1} = P_q + \Delta P \quad (11)$$

Symbol	Meaning
P_q	Population at time q
ΔP	Fixed population growth

The structure of the equations defined after the developer's objective function (equations 3 to 11) reflects the assumed influence of each parameter involved. Their algebraic structure was defined in the most convenient form for the model's goals, without loss of generality.

At each time q the following algorithm is performed:

1- Assume that from the previous round (at time $(q-1)$) $P_{Homeless}$ families were not able to find dwelling units in the city ($P_{Homeless} \geq 0$)

2- There are parcels already purchased but still not developed. If the waiting time $\tau(x,h)$ elapses now, they are developed (Equations 1 and 2). Assuming that there are v parcels which fulfill this condition, this means that $(h_1 + h_2 + ... + h_v)$ new dwelling units are entering into the market.

3- The supply is updated. If at the end of the previous round it was S_{q-1}, it is now $S_q = S_{q-1} + h_1 + h_2 + ... + h_v$

4- Since population growths by ΔP, (according to equation 11) the demand is composed by families without dwelling from the previous round, and newer residents:
$D_q = P_{Homeless} + \Delta P$

5- If $S_q \geq D_q$ then D_q dwelling units are purchased at price $WTP_{q-1}(x)$

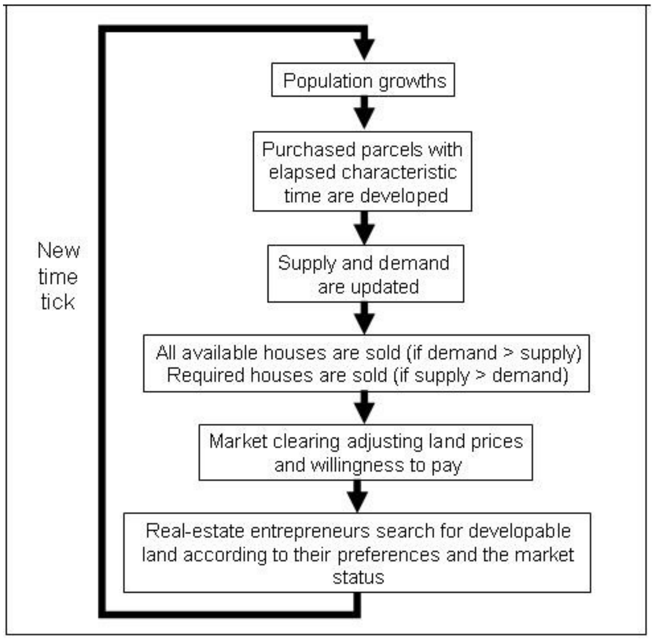
6- If $S_q < D_q$ then S_q dwelling units are purchased at the same price

7- The land price $I_q(x)$ and the willingness to pay $WTP_q(x)$ are updated on all available parcels x in the grid (according to equations 4 to 10)

8- Both patient and impatient developers search for new investments within the available parcels left in the grid, according to equations (1) and (2). Patient developers take decisions according to maximal profit. Impatient developers calculate the maximal profit too, but need to take into account whether the optimal investment will last more than time T or not. If $\tau > T$ the development intensity h must be reduced in order to achieve $\tau = T$

9- $(m+n)$ parcels purchased by patient and impatient developers during time q initiate their waiting time towards approval

The following picture presents a simplified flow chart of the process:



The model reflects a free dwelling market mechanism driven by developers' profitability maximization under constraints. Prices updates according to the relative changes in supply and demand over time, and the market clears in the sense that dwelling units available anywhere in the grid are purchased at a price partially defined by the parcel location.
At this stage, planning authorities are modeled only by means of the characteristic time defined initially for each parcel in the grid. Their behavior over time and the mutual

relationship with developers and city's population is still not defined. Even before adding these elements to the model, a number of potential pitfalls become evident.
The equations defined previously are very detailed and explicit. They are useful as a first step for building a spatial housing market model able to simulate dynamic evolution of supply, demand and prices over time. However, inasmuch the model's objective is to analyze the combined effect of urban planning policies and the choices of real-state entrepreneurs, it results overelaborated in its current form. First, because the number of parameters required for defining the model are large. Second, because in order to create a realistic simulation, all those parameters need to be estimated correctly. Some parameters are relatively easy to assess (for example, the construction cost equation's coefficients) but others are difficult to estimate, as land prices and willingness to pay decay exponents. The assessment effort is hardly justified in light of the research objectives. Moreover, profusion of parameters leads to weaker results. Since each one of the parameters can be modified, small changes in a single parameter can lead to a substantially different qualitative behavior. For example, in the present model, adjusting the minimal willingness to pay value near the construction costs can lead to a freezing state in which nothing happens for ever or to a mono-centric urban behavior. The same effect is possible with slight changes in each one of the attraction decay exponents by separate or even in the ratio between them. Under those conditions, the system behavior is consistent only in a narrow space defined by tiny acceptable parameters ranges. Here the focus is set on few dynamic behaviors which are qualitatively the same over a wide range of parameter's changes. More specifically, the focus is on the interaction between developers' choices, planning policies and demand for dwellings, and how these can lead to the creation of new urban sub-centers. Elements as non-spatial-related land cost and dwelling prices evolution are secondary in light of the previously stated objective. Therefore, a new simpler and more adequate model was defined.

3.3. Agent based & cellular automata model

The purpose of this model is to incorporate planning decisions into an agent-based simulation model that yields realistic urban spatial structures. This is necessary because the combined effect of urban planning policies and regulations and the choices of developers searching for real estate projects can explain much of the urban spatial-temporal evolution. Firm characteristics, and in particular the time impatience of land developers, interacts with time-related municipal development strategies and in turn, affects the urban spatial structure dynamics.

Planning authority sets rules concerning the location and intensity of developable land. The assumption is that planning building restrictions grow with distance from the CBD. These restrictions are expressed as a monotonically increasing function of the time required for obtaining construction permits as the distance from the CBD increases. From the developers' point of view this is the time spanning between acquisition of property rights and the realization of returns (the characteristic time of a given location). Developers select preferred locations for buildings and the intensity, or height, of buildings. As explained in the previous sections there are two types of real estate developers, patient and impatient.

Developer's objective functions (1) and (2) still holds, but several assumptions were made:

1- At any given time, in each location of the grid, the difference between land prices and willingness to pay for dwelling are such that some profitability margin exists for any development project. This profitability margin exists after subtraction of construction costs, for any reasonable development intensity. "Reasonable" means that the building height will not cause the project waiting time to be higher than twice the characteristic time of the parcel (a more detailed explanation of this issue in next points). Still, developers are profit maximization seekers, and they will choose the location and the intensity according to the objective function.

2- The characteristic time is a function of location and height:

$$\tau(x,h) = \tau_L(x) + \tau_H(h)$$

Although the $\tau_L(x)$ term is defined by the city planners, the $\tau_H(x)$ term is an endogenous decision of the developer and is proportional to the project height.

3- As a corollary, the building height is not a limitation factor for developers (either patient or impatient). The only limitation factor is the characteristic time imposed on height by planner's boards.

As a result from these assumptions, a large set of parameters from the previous model are redundant in this redefined settings. All price related parameters are not more necessary, and the model is driven by characteristic time settings and attraction forces between all the cells in the grid, whether developed or not.

In this case, the model has less parameters than the previous one. In addition, it is much less sensible to parameter changes. In the presence of one homogenous group of patient developers the urban structure results in an Alonso-type mono-centric city. When both patient and impatient developers are present, adversarial interactions between the planning authorities, the different developers' types and the dwelling demand starts dynamical processes which leads to urban sub-centers emergence.

A full description of the model is offered in the paper "Polycentric urban dynamics - heterogeneous developers under certain planning restrictions ", and "Bursts and avalanches – the dynamics of polycentric urban evolution", both included in the "Findings" chapter.

3.4. Dynamic analyses and Self Organizing Criticality

Self-Organized-Criticality (SOC) is a concept that was developed in order to describe non-equilibrium systems that respond to external perturbations with events of all sizes and no apparent characteristic scale. According to Per Bak "… systems evolve to the complex critical state without interference from any outside agent …Large catastrophic events occur as a consequence of the same dynamics that produces small ordinary everyday events." (Bak, 1996). The sand-pile metaphor is commonly used to illustrate conceptually SOC ideas (Bak, 1996; Christensen & Moloney, 2005). A wide range of SOC applications were developed in fields as diverse as physics (Christensen & Moloney, 2005, Dickman et al, 2000, Dhar, 2006; Bak et al, 1987, 1988; Bak, 1990, Carlson & Swindle, 1995), time series analysis (Xianzhong & Sheng, 2010) and cellular automata models (Bak et al 1989, Alstrom & Leao, 1994; Sales, 1993). There were some attempts to examine SOC relevancy to urban systems through fractal measurements (Batty & Xie, 1999) and exponential functions that define hierarchical structures of city systems (Chen & Zhou, 2008).

At the urban scale, the complex dynamics created by the adverserial interaction of land developers and planning authorities described in the agent-base model from the previous section cause dynamics simmilar to those created by Self Organizing Criticality models. When plotting the distribution of the construction activitiy in the previous model, it is expected that there will be very many small bursts and relatively few large ones. This type of situation is reminiscent of SOC phenomena. The agent-based model described previously demonstrates that the rules that govern the planner's behavior lead to the emergence of small clusters of buildings of various heights in peripheral sites. When such clusters become concentrated enough, city planners realize that the slow high-rise building permissions dripping created the seed of a new urban sub-center, and that the specific peripheral zone will become urbanized. The municipality then relaxes the characteristic time constraints in that zone, setting it lowest in the new cluster, and gradually increasing it outwards. A large set of new locations with new opportunities both for patient and impatient developers arise. Both devote themselves to the new sub-center development, giving rise to a construction boost which continues until the new sub-center is fully developed, followed by a stagnation period, when the whole process is expected to happen again.

The burst phenomenon is due to the fact that planning authorities are bounded by land-use zoning and otherwise resist granting building permits for developments at the city's edge. Population growth and consequent excess demand for housing that does not receive response within the city's boundary creates pressure for granting of building permits beyond the planned zones and leads to the establishment of new centers of urban development. Once the building process starts, the initial big developer is joined by others, including small developers, and a significant sized burst occurs.

A discussion about the Self Organizing Criticality implications of the model is offered in the paper "Bursts and avalanches – the dynamics of polycentric urban evolution", included in the "Findings" chapter.

4. Findings

4.1. Paper #1

Developers' choices under varying characteristic time and competition among municipalities

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Abstract

In a previous paper (Czamanski & Roth, 2011) we demonstrated that spatial variation in characteristic time, defined as the time between acquisition of property rights and the realization of returns, can lead to leapfrogging and scattered development, especially during periods that interest rates are low or negligible. We explained this result by modeling the simple behavior of developers in the context of a single, linear city. In this paper we consider the case of two municipalities in which development policies, activities of non-governmental organizations and neighbors' behavior result in spatially varying characteristic time functions. Myopic behavior, in the sense that each city is interested only in what happens on its side of the municipal boundary, lead to unintended leapfrogging. Whereas competition between the cities, including in the case that each city takes into consideration processes in the entire region, results in intentional leapfrogging or in spatially concentrated development.

Introduction

Much of the literature concerned with the spatial structure of cities analyzed patterns in the context of Alonso type models [Alonso, 1964; Mills, 1967; Muth, 1969; Wheaton, 1974]. In contradistinction, high-rise buildings display a peculiar non-continuous spatial pattern along various rays emanating from urban centers outwards. In a recent paper we studied these patterns in the case of Tel Aviv [Czamanski et al, 2009]. In another recent paper [Czamanski and Roth, 2011] we suggested a plausible explanation for evolution and the resulting pattern.

In particular, our model suggests that the effort of municipalities and of various NGO's to prevent sprawl may be counterproductive and that under some circumstance it may contribute to the creation of edge cities [Czamanski and Roth, 2011]. We introduced the concept of characteristic time, the time between acquisition of property rights and the realization of returns, as a fundamental factor in a model of developers' behavior. According to our model, the evolution of urban spatial patterns is the result of developers' search process for parcels of land that can yield the highest returns. One of the critical variables in the decision-making of developers is time. Despite obvious differences in land prices within a particular real estate market, differences in costs and prices are relatively small in comparison to differences in their value due to their time incidence.

In our previous paper we considered the presence of a single municipal authority and one set of stable rules that determined the spatial incidence of characteristic time. In this paper we extend the analysis to the case of two cities. Here the spatial incidence of characteristic time is determined by a municipality within its own boundary, independently of its neighbors. The characteristic time in each authority is an outcome of the behavior of several interacting actors and agendas, including the municipality's planning authorities, neighbors' idiosyncrasies, NGOs' agenda and others. For example, in a city where the municipality leads an anti-sprawl policy and residents and environmental groups are active in efforts to preserve open spaces, the characteristic time will presumably rise from the center outwards. In a city where the CBD lacks sufficient infrastructure to support urban growth, as may the case in an historical city center, both the municipality, and neighbor associations may support spreading development, and therefore the characteristic time will be high near the center and decrease with the distance from it. We then study the repercussions of various models of rivalry and cooperation of the municipal authorities and the resulting implications for the behavior of developers and for the spatial structure of cities.

One city case

In a context of a linear city and in the presence of a single municipality the phenomenon of leap-frogging varies in relation to changes in characteristic time over space. Figure 1 presents the stylized facts in the case of a simplified linear economy. The central business district (CBD) is at X_A. The city extends to a boundary at X_L. The developer chooses to build at location D at a distance X from the CBD. For the present we ignore the presence of another municipality with a CBD at X_B.

The developers' problem is to find an optimal location x* and optimal height h* that leads to profit maximization. The developer's objective function [Czamanski & Roth, 2011] is:

$$\begin{aligned} &MaxFV(t=\tau) = -I(x,h)(1+r)^{\tau} - C(h) + P(x)h \\ &x,h \\ &s.t.\tau = \tau(x,h) \end{aligned} \quad (1)$$

Where *I(x, h)* represents that land price as a function of location x and building rights expressed as height of buildings. The discount rate is *r*. The overnight building cost is a function of building height and is expressed as *C*. Finally, *P(x)* is the willingness to pay of buyers at location *x*.

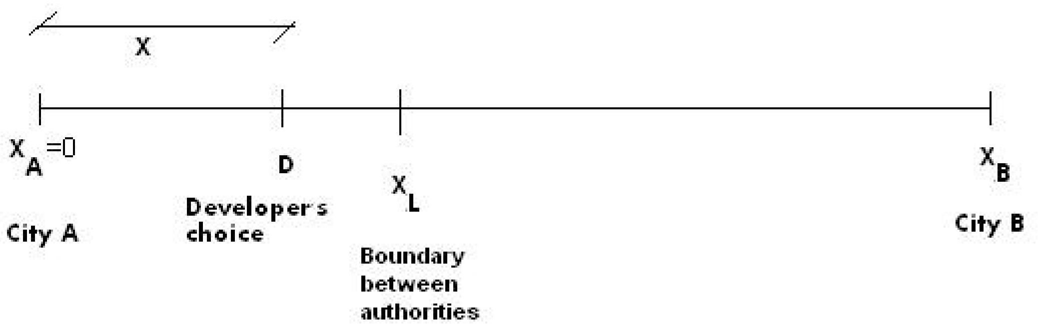

Figure 1: The spatial structure of linear cities

Analyzing the first order conditions for identifying the optimal location and height Czamanski & Roth arrived at the following conclusions:

1. Leapfrogging of heights occurs when

$$\frac{\partial h^*}{\partial \tau} > 0 \text{ and } \frac{\partial \tau}{\partial x^*} > 0 \text{ therefore } \frac{\partial h^*}{\partial x^*} = \frac{\partial h^*}{\partial \tau} \cdot \frac{\partial \tau}{\partial x^*} > 0 \quad (2)$$

2. There are three distinct possibilities for the sign of $\frac{\partial \tau}{\partial x^*}$:

$$\frac{\partial \tau}{\partial x^*} = 0 ,\ \frac{\partial \tau}{\partial x^*} > 0 \text{ or } \frac{\partial \tau}{\partial x^*} < 0$$

3. If $\frac{\partial \tau}{\partial x^*} = 0$ then in (2) $\frac{\partial h^*}{\partial x^*} = \frac{\partial h^*}{\partial \tau} \cdot 0 = 0$. In this case the optimal height does not depend on the distance from the CBD.

4. If $\frac{\partial \tau}{\partial x^*} > 0$, then the sign of $\frac{\partial h^*}{\partial \tau}$ in (2) is not clear and the condition for a positive derivative that can lead to leapfrogging is a very low interest rate, such as may occur during periods of recession.

5. If $\frac{\partial \tau}{\partial x^*} < 0$ it can be shown that $\frac{\partial h^*}{\partial \tau} > 0$ and therefore $\frac{\partial h^*}{\partial x^*} = \frac{\partial h^*}{\partial \tau} \cdot \frac{\partial \tau}{\partial x^*} < 0$. In this case, h* is a decreasing function of the distance from the CBD. As in the previous case, only when the interest rate is negligible leapfrogging is possible.

The above results are suggestive of the importance of planning decisions that result from the behavior of urban actors and their implications for the spatial structure of an isolated city. Now we turn to the more realistic situation of non-isolated urban context.

The case of two cities

Most cities, at least in the western world, are segmented into many municipalities. In our linear world, X_L (see Figure 1 above) is the administrative boundary between the two municipal administrative areas A and B. For our present purpose the location of this boundary is insignificant. It is assumed that it was defined as part of an historical, political process. The segment $(X_L - X_A)$ and the segment $(X_B - X_L)$ are not necessarily equal.

The planning authorities' decisions are influenced by policies, regulations and not the least by the intervention of NGOs and the public in the decision making process, and therefore, in each municipality the characteristic time is determined by the interaction of an independent planning authority and of others involved in the planning process. We presume that in a Tiebout [Tiebout, 1956] style world, each planning authority reflects the preferences of its self-selected residents. The characteristic time in each municipality pertains to its own territory only. As in the single municipality case, τ is function of distance from the respective central business district. It is also a function of the intensity of the proposed development. Thus, it is an increasing function of building height. In other words:

$$\tau = \tau(x,h) \qquad \begin{cases} \tau^A(x,h) & \text{If } x \in [x_A, x_L] \\ \tau^B(x,h) & \text{If } x \in (x_L, x_B] \end{cases} \qquad (3)$$

As in our previous paper, it is assumed that the developers have precise information about the characteristic time at each location over the segment $[x_A, x_B]$.

Since the present analysis is concerned with two neighboring municipalities, each of which defines the characteristic time in its respective area of influence, various possible situations occur and should be examined. First, we assume myopic actors in each municipality. Myopic behavior means that each actor (planners, NGO's, citizens) acts as if what happens beyond his municipal boundary is not of his concern. All the possible combinations of characteristic time functions need to be analyzed. The following table lists the various possibilities.

Municipality A	**Municipality B**
$\tau_x^A = 0$	$\tau_x^B = 0$
$\tau_x^A > 0$	$\tau_x^B = 0$
$\tau_x^A < 0$	$\tau_x^B = 0$
$\tau_x^A > 0$	$\tau_x^B > 0$
$\tau_x^A < 0$	$\tau_x^B > 0$
$\tau_x^A < 0$	$\tau_x^B < 0$

Table 1: Characteristic time scenarios in the case of two cites and myopic planners

Relaxing the myopic behavior assumption, all the actors in both municipalities are aware of the prevailing characteristic time throughout the entire $[x_A, x_B]$ segment, irrespective of the jurisdiction that determines τ. Two possible situations arise. The situations depend on each municipality's planning goals and policies regarding the desired behavior by developers. Should their policies differ, such as for example as one city aims to spread its development and the other attempts to concentrate building areas and maximizing open areas, each of the cases included in Table 1 should be reexamined. If the policy outcomes of the municipalities are similar, they will compete in order to maximize their objectives, either by attracting developers or by imposing stricter restrictions. In this case, it is expected that their τ functions will reach an equilibrium where

$$\lim_{x \to x_l} \tau^A(x,h) = \lim_{x \to x_l} \tau^B(x,h)$$

In such a case the characteristics of the equilibrium function should be analyzed regarding the position of the boundary limit (x_L) too. It is possible that one of the cities will suffer disadvantaged position due to the location of the boundary and regardless of the equilibrium that can be achieved theoretically.

So far we considered cities A and B that were implicitly assumed to be of equal size. If their size differ and this element is included in the analysis, gravitation considerations arise that can influence developers' decisions. For example consumers demand characteristics and willingness to pay for a house at the same distance from the CBD of a large city or the CBD of a smaller one will differ.

Myopic behavior

The trivial assumption that $\tau_x^A = 0$ and $\tau_x^B = 0$ means that planning policies and urban actors' behavior are place independent in the case of both cities. In other words, in each city characteristic time does not depend on location, nor is it dependent on the optimal height of proposed building projects. The developer's decision concerning where and at what intensity to build is not influenced by the location on the segment $[x_A, x_B]$, but by other parameters, not considered in this model.

Similar result holds in the cases where $\tau_x^A > 0$ and $\tau_x^B = 0$ or $\tau_x^A < 0$ and $\tau_x^B = 0$. In such a case in one of the cities location specific planning policies arise, while the other is insensitive to location in planning policy making. In this case the model is capable to incorporate the characteristic time laws only in $[x_A, x_L]$ segment of the market, whereas in $[x_L, x_B]$ the characteristic time does not depend on location. It may well be that some non-location related features in city B will make development there much more profitable than in $[x_A, x_L]$. However, nothing can be said about this possibility within this model framework.

Now we consider the case that $\tau_x^A > 0$ and $\tau_x^B > 0$. This means that the characteristic time increases with the distance from the CBD in both cities. This indicates that planning policies in both cities aim to concentrate urban development near the CDB and to prevent sprawl. The further away from the CBD the proposed project is located, the more cumbersome is the approval process, due to bureaucratic impediments or legal objections, and the more time it will take to realize a return on the developer's investment. It seem reasonable to suppose that the characteristic time increases at a decreased rate (therefore $\tau_{xx}^{A} < 0$ and $\tau_{xx}^{B} < 0$). Figure 2 below describes the general resulting scenario.

A developer ready to wait for the realization of the project until time t_1 will be indifferent between locations x_{A1} and x_{B1}. This conclusion requires the assumption that land and overnight construction costs are similar. The resulting situation holds for any location within the segment $[x_A, x_L]$ and the segment $[x_{B_{Max}}, x_B]$. The developer will choose a site within those segments, as close as possible to each of the CBDs. The possibility of leapfrogging in each city is present in the case that interest rates are low enough to lead to $I \cdot \ln(1+r) \cong 0$.

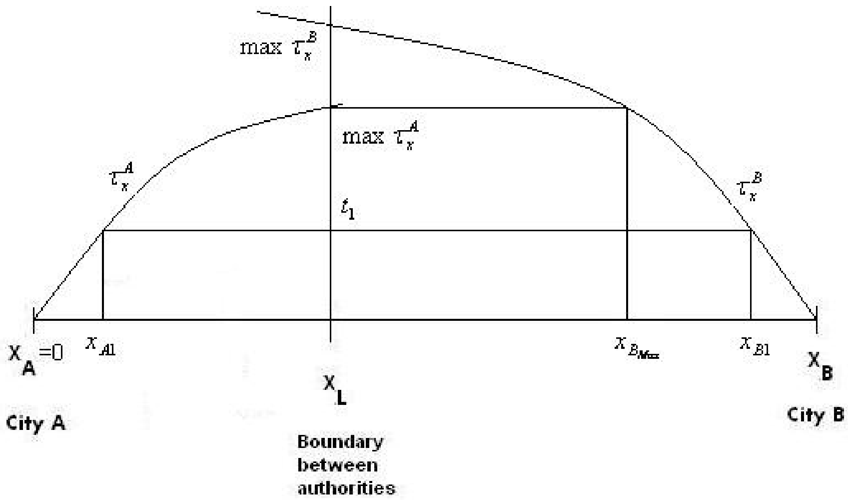

Figure 2: Two cities case with $\tau_x^A > 0$ and $\tau_x^B > 0$

Within the segment $[x_{B_{Max}}, x_L]$ the outcomes of this scenario depend on the initial investment required in this area. If it is low enough to overcome the longer characteristic time, the developer is expected to choose a site in $[x_{B_{Max}}, x_L]$, even at the expense of options sited in $[x_A, x_L]$ or $[x_{B_{Max}}, x_B]$. Otherwise, if the initial investment is comparable to the investment required in $[x_A, x_L]$ and $[x_{B_{Max}}, x_B]$, given the different behavior of both τ_x^A and τ_x^B curves none of the available sites in the whole segment $[x_{B_{Max}}, x_B]$ will be chosen (at least as long as there is available land on $[x_A, x_L]$ or in $[x_{B_{Max}}, x_B]$). This is because the characteristic time imposed in it by municipality B is too high.

If $\tau_x^A < 0$ and $\tau_x^B > 0$, the characteristic time decreases with the distance from the center of A, but the opposite is true starting from B's center and moving away from it. This situation may suggest that for some reason, city A is willing to spread its development far from its own CBD, while city B takes the opposite approach, trying to concentrate the urban development near its CBD. A schematic depiction of this scenario is presented in Figure 3.

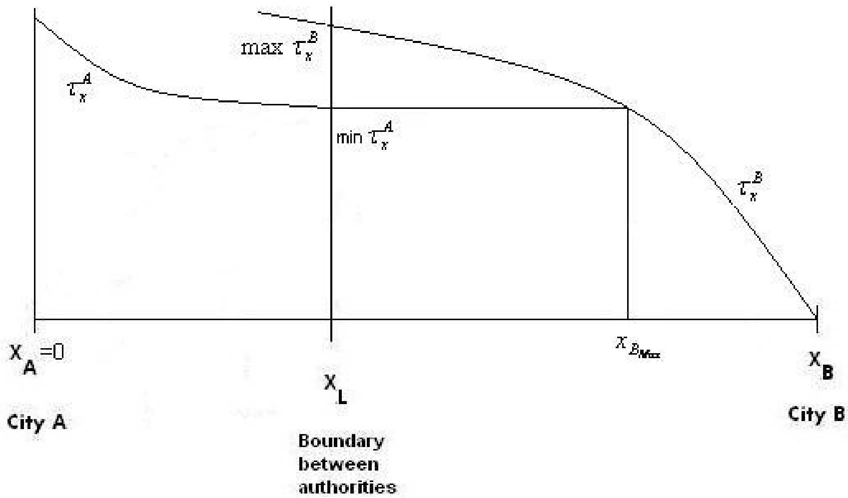

Figure 3: Two cities case with $\tau_x^A < 0$ and $\tau_x^B > 0$

In this case, assuming interest rates far from zero ($r >> 0$) and similar initial investments in $[x_A, x_B]$, the developer will always choose locations sited in $[x_{B_{Max}}, x_B]$, since here the characteristic time is lowest. Development asymmetries between cities A and B can be created, and, following the myopic assumption, city A is expected to lower significantly its characteristic time in order to attract developers. Under the scenario assumptions, this policy is prone to failure. Reducing the length of $[x_{B_{Max}}, x_B]$ is the only expected result, but our developer will not be attracted to city A boundary, unless there is no available land on $[x_{B_{Max}}, x_B]$.

Still under the same assumptions, if the initial investment is assumed to be a decreasing function of the distance from the CBD ($I_x < 0$), another outcome can result. The developer should maximize profits performing higher investments and selling high price houses near the CBD (in this case B is the best option due its low characteristic time) or performing lower investments and selling at a lower price in other locations. In this last case, the gap in the characteristic time in the limit x_L may determine that the developer willing to build near the border zone will search for a location closer to the city A side of the limit, leading to leapfrogging as is indicated in figure 4 that includes three superposed graphs as functions of x: τ_x in time units, I_x in land price units and a sketch of the three preferable locations from the developer's point of view.

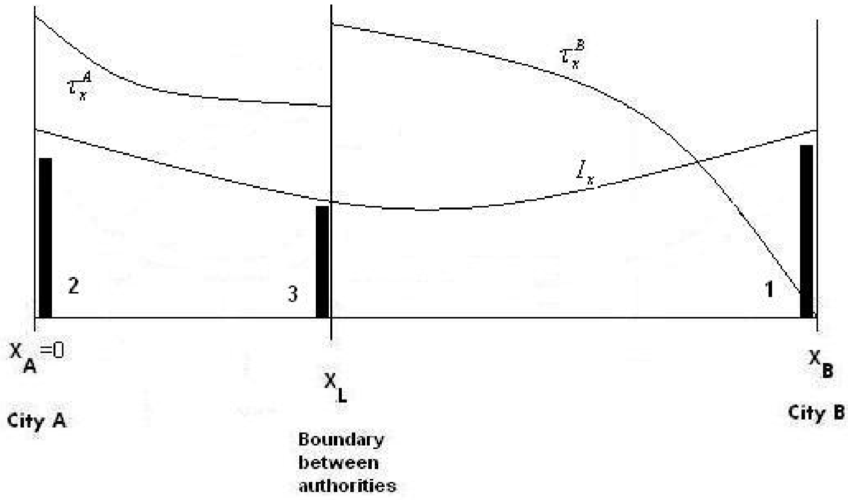

Figure 4: Two cities case with $\tau_x^A < 0$ and $\tau_x^B > 0$ and $I_x < 0$

If interest rates are negligible, leapfrogging conditions may appear along the entire segment $[x_A, x_B]$, since both if $\tau_x^A < 0$ and $\tau_x^B > 0$ the low interest rates can lead to developments far from both CBDs.

The last case pertains to $\tau_x^A < 0$ and $\tau_x^B < 0$. This scenario suggests that both cities are encouraging developers to find locations far from the CBD. A schema of τ_x is included in the next figure.

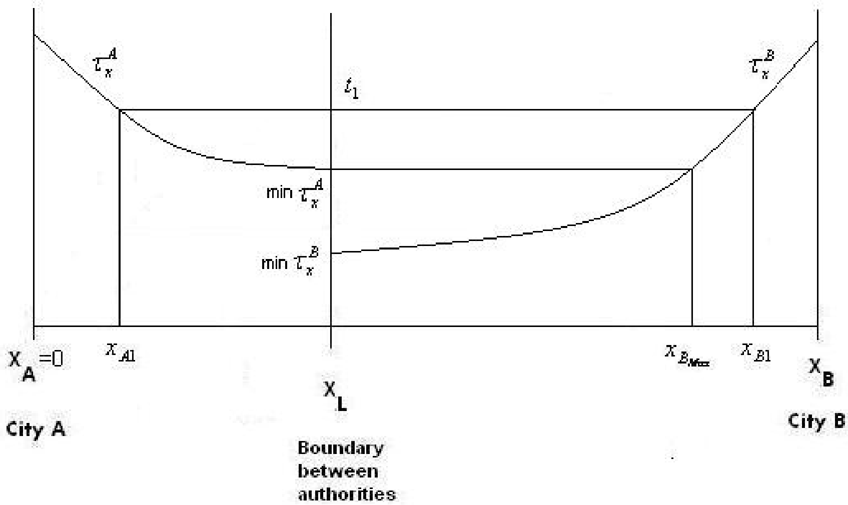

Figure 5: Two cities case with to $\tau_x^A < 0$ and $\tau_x^B < 0$

A developer, who is ready to wait until t_1, will be indifferent between locations x_{A1} and x_{B1} if land and overnight costs are similar. This situation holds for any location between $[x_A, x_L]$ and between $[x_{B_{Max}}, x_B]$. However, the lowest characteristic times can be found within segment $[x_{B_{Max}}, x_L]$. Assuming a normal situation that includes positive interest rates and land prices that are a decreasing function of the distance from the CBD, $I_x < 0$, the result should be similar to those depicted in Figure 4, but in this scenario with the development will occur on the city B side of the border, where $\min \tau_x^B < \min \tau_x^A$. Leapfrogging of high buildings can occur as in the previous scenarios, if interest rates are very low, and in this case, because the gap in the characteristic time near the boundary x_L, high buildings are expected to be built on the city B side of the border.

Full awareness – Competition

Assuming that both municipalities are aware of the tendencies and processes occurring in the entire $[x_A, x_B]$segment and given that their outcome development policies are similar, they will compete in order to pursue their similar goals. In this case, not only the shape of the characteristic time (τ_x^A and τ_x^B) is important, but so is their behavior near the boundary x_L.

If τ_x^A and τ_x^B have significantly different values in x_L ($\tau_x^A(x_L) >> \tau_x^B(x_L)$ or $\tau_x^A(x_L) << \tau_x^B(x_L)$), developers behavior around the boundary will be heavily influenced by the difference, seeking development sites on one side of the border, presumably the side with lower characteristic time. Competition between the municipalities will lead to characteristic times that ensure that developers will be indifferent between both sides of the boundary. In other words, that

$$\lim_{x \to x_l} \tau^A(x,h) = \lim_{x \to x_l} \tau^B(x,h)$$

Again, let's look at the case when $\tau_x^A > 0$ and $\tau_x^B > 0$, as depicted in figure 6.

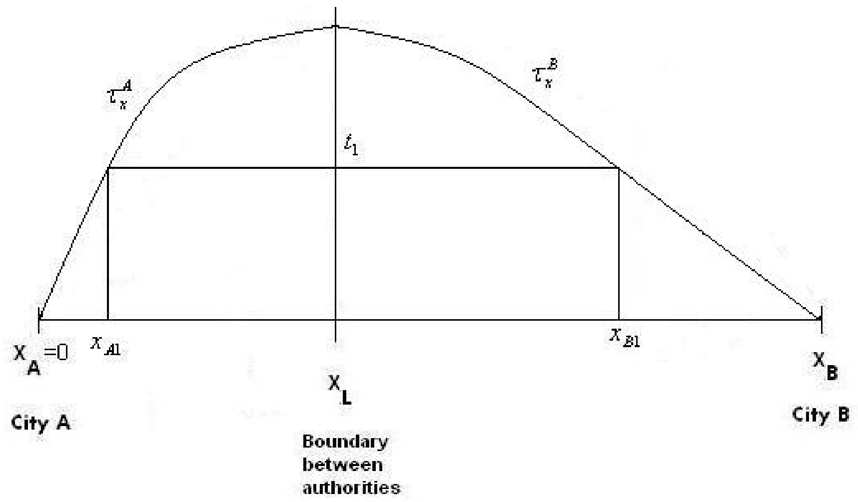

Figure 6: Two cities case with $\tau_x^A > 0$ and $\tau_x^B > 0$

Given that land and overnight costs are similar, a developer ready to wait until time t_1 will be indifferent between locations x_{A1} and x_{B1}. In this case, assuming normal market conditions, leapfrogging conditions can arise depending on τ_x^A and τ_x^B concavity and x_L position. The behavior of the functions at x_L boundary and the assumption that $\tau_x^A > 0$ and $\tau_x^B > 0$ do not assure similar growth rates as τ_x^A moves away from x_A and τ_x^B moves away from x_B. For example, in Fig. 6, decision to develop at x_{B1} could cause leapfrogging in city B, whereas a similar decision at x_{A1} may not. This is despite the fact that from the developer's point of view the decisions are equivalent.

If it is assumed that $\tau_x^A < 0$ and $\tau_x^B < 0$, and a similar relationship between τ^A and τ^B second derivatives and x_L location can be defined. It is related to the functions' concavity.

In Figure 7, development in locations x_{A1} or x_{B1}, both with the same characteristic time t_1, can lead to leapfrogging in city B if x_{B1} is chosen, but probably not in city A if site x_{A1} is developed instead.

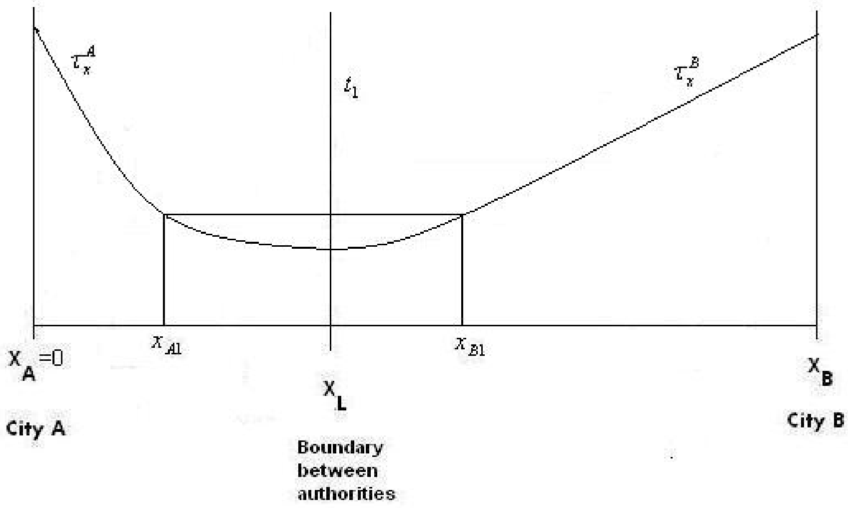

Figure 7: Two cities case with $\tau_x^A < 0$ and $\tau_x^B < 0$

The basic assumption in this section is that the development policies in city A and city B are similar. Suppose that unwanted leapfrogging conditions are created on one side of the administrative boundary. This means that the municipality or other urban actors will provoke a change in the characteristic time function in order to encourage developers to search for developable land in other parts of its segment. It implies, in turn, that the other municipality and the agents acting in it will be forced to change their own characteristic time function, in order to avoid the creation of leapfrogging conditions in their segment. The same interactions hold if the leapfrogging is a positive outcome from the municipalities' point of view, but in this case they will compete giving the best possible conditions to develop land far from the CBDs.

It follows that in the long run, it is expected that both τ^A and τ^B will converge to an equilibrium characterized by the rule that for every characteristic time t_n, there are $x_{A_n} = \tau_x^A(t_n)$ and $x_{B_n} = \tau_x^B(t_n)$ such that

$$\frac{x_{A_n} - x_A}{x_L - x_A} = \frac{x_B - x_{B_n}}{x_B - x_L}$$

In other words, the optimal location for each characteristic time at both sides of the administrative boundary will be proportional to the municipality's segment length. The previous condition holds both for the case when both $\tau_x^A > 0$ and $\tau_x^B > 0$, and opposite ($\tau_x^A < 0$ and $\tau_x^B < 0$).

Irrespectively of policies and shape of the characteristic time functions, negligible interest rates could provoke leapfrogging along the entire $[x_A, x_B]$ segment, as stated in (3).

Situations where $\tau_x^A < 0$ and $\tau_x^B > 0$, or where $\tau_x^A < 0$ and $\tau_x^B > 0$, are not relevant under the assumption that the resulting development policies of both municipalities are similar. This is because they define different management approaches at each side of the border.

Full awareness – Different policies

An additional plausible assumption is that both municipalities are aware of the tendencies and processes occurring in the entire $[x_A, x_B]$ segment, but that their resulting development policies are different. For example, if city A is willing to develop low-density sprawling neighborhoods and city B wants to maintain a highly concentrated business district with plenty of open space in its periphery, a situation as depicted in Figure 3 could arise. Since the boundary between A and B is irrelevant for the people living in segment $[x_A, x_B]$, such an arrangement could be mutually beneficial, from a regional point of view, offering simultaneously dense urban environment, low-density neighborhoods and open spaces, and for both cities, one attracting dwellers and the other attracting business and offering recreational services.

Conclusions

We have demonstrated that spatial variation in characteristic time can lead to leapfrogging and scattered development, especially in times that interest rates are low or negligible. This phenomenon can be explained by modeling the simple behavior of developers in the context of a single city within a linear space (Czamanski & Roth, 2011).

The same situation can arise if the model includes two cities with linear edges. But in this case, additional factors play an important role and need to be considered. The main difference from the single city case is that in each city, different development policies can arise, that are reflected in different characteristic time functions in each territory. Myopic assumptions, in the sense that the urban actors in each city are interested only in what happens on their side of the border, can easily lead to unintended leapfrogging. Whereas competition between the cities, including in the case that all the factors involved in planning processes in each city take into consideration processes in the entire region, can result in intentional leapfrogging or in spatially concentrated development, depending on the outcoming policy objectives of the authorities. Additional scenarios of collaboration between authorities with different goals are also feasible.

In this paper and in all the scenarios discussed, the core cities A and B were assumed to be equivalent in each relevant parameter, such as population, size, purchase power, etc. The only element that caused asymmetries between the cities was the location of the administrative boundary. Besides its simplicity, there is no reason to assume that this is the case. Both cities can be different, even qualitatively, such as for example, a developed city in A and a small town in B. This and other cases will be considered elsewhere.

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4.2. Paper #2

Cities in competition, characteristic time and leapfrogging developers

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Abstract

In a recent paper Czamanski and Roth (2011) demonstrated that because the profitability of construction projects is influenced by variations in the time incidence of costs and revenues, despite of declining willingness-to-pay and land gradients with distance from central business districts, profitability can experience local maxima away from urban centers. The time until the realization of revenues was termed "characteristic time". Its size is the result of planning polices and can lead to leapfrogging and scattered development, especially when interest rates are low or negligible. We explained this result by modeling the simple behavior of developers in the context of a single linear city.

In this paper we consider the case of two municipalities with different development policies and characteristic time functions. We explore local maxima in profitability, typical of disequilibrium situations, especially during periods that cities are growing. Myopic assumptions, in the sense that each city is interested only in what happens on its side of the municipal boundary, can easily lead to unintended leapfrogging. Competition between the cities can result in intentional leapfrogging or in spatially concentrated development, depending on the policy objectives. We extend the analysis further and consider qualitatively different cities that give rise to different gravity-type forces and differences in willingness to pay. The demand and supply sides of the building market are integrated into the model. The additional considerations can lead to various patterns of scattered development capable of explaining the spatial structure of metropolitan areas.

Introduction

Urban spatial development is the subject of many books and hundreds of papers. In simple Alonso type models (Alonso 1964, Mills 1967, Fujita 1989) people and activities that agglomerate in cities to benefit from mutual proximity compete for space and locations (Duranton et al 2004, Zenou 2009). Preferences are represented by a demand for geographic locations in relation to city centers. The winners are willing to and able to pay more than others for this proximity. As a result land rents at the city centers should be high and should decline from this location outwards. We should observe monotonically decreasing land rents and density as the distance from the urban centers increases.

Empirical tests of these models utilized crude tools and averaged data to estimate rent gradients and decreasing exponential functions to depict urban spatial structure (Alperovich 2000). The resulting empirical regularity is true at the crudest resolution only. Even casual empiricism suggests that at a finer resolution the evidence is quite different. There is growing body of evidence that urban spatial dynamics are discontinuous in space and non-uniform in time (Benguigui et al 2000, 2001a, 2001b, 2004a, 2004b, 2006). The evidence suggests that in each period there is a proportional addition of buildings in each height category. The findings indicate a seemingly random spatial dynamics of high-rise buildings (Benguigui et al 2008).

It is noteworthy that the classical models focused on the demand side of the market only. The vast majority of the various elaborations and applications ignored the supply side, the considerations of planners and developers and the characteristics of locations. The classical models assumed homogeneity of consumers and of producers except for one parameter – the consumers' willingness to pay for proximity to the urban center, or to secondary centers in the urban space.

If the elasticity of the demand functions was low relative to the elasticity of the supply, then the responsiveness of the quantities of buildings to changes in demand parameters would be high. This is not the case in typical real estate markets and definitely not the case in the high-rise buildings market. In these markets there are many consumers and very few suppliers or developers. The influence of the consumers on quantities and prices is low and therefore the aggregate demand curve is very flat and elastic. The supply curve is much less elastic. These market conditions yield high dependence on the supply side and its characteristics. Uncertainties of this side which represents the behavior of developers and planners can cause high and unexpected fluctuations in the quantities of high-rise buildings. This in turn can influence and support random statistical and spatial processes. There is a need for an alternative approach that can explain the basic factors responsible to these uncertainties.

Following the seminal paper by Krugman (1991) and the birth of new economic geography, uneven spatial development became an object of renewed and intensive interest. Spatial evolution has been studied at a variety of scales. At each scale it is related to different agglomeration forces that create spatial inequality. According to Fujita and Thisse (2008) the underpinning forces are often the result of "strong tensions between different political bodies or jurisdictions". The jurisdictions create the rules of the playing field within which preferences of individuals lead to decisions and create spatial order. In the urban context, the land market constitutes the playing field. It serves to allocate both economic agents and activities across space.

In this paper we follow Henderson and Venables (2008) and argue that developers consider the preferences of consumers and that the behavior of builders determines the spatial structure of cities. This behavior can reflect various objective functions and spatial conditions within which the decisions are made. Following Czamanski and Roth (2011) we present a simple model of the behavior of developers. We then study the repercussion of the developers' behavior for the spatial structure of cities under various assumptions concerning the environments within which their decisions are made.

In a companion paper we studied the case of two adjacent jurisdictions, each with its own characteristic time function, myopic behavior of planners and lack of rivalry among the jurisdictions (Broitman et al 2011). In this paper we extended further this theoretical framework. We study both the supply and demand sides of the housing market within a linear space bounded by two qualitatively different cities. The supply side is represented by the developer's behavior, influenced by planning regulations, and the demand side is expressed by the willingness to pay for a house as a function of the gravity-type forces.

The paper consists of 5 additional sections. In section 2 we present the motivation for the analyses that follow by means of data for Tel Aviv indicating an urban structure that is discontinuous in space and non-uniform in time. In section 3 we present the basic model of developers' behavior, we explore the consequences of different developers’ strategies and describe the case of two neighboring, similar cities. In section 4 we describe the case of two qualitatively different neighboring cities without competition. In section 5 we present the case of competition among unequal cities. Some conclusions follow in the last section.

The 3D structure of Tel Aviv

Tel Aviv is the second biggest city in Israel and it is a part of a large metropolitan area (Gush Dan) that consists of a number of big municipalities. The initial development of Tel Aviv took place in the early years of the 20th century. But, until the 1970's Tel Aviv was a flat city with very few high-rise buildings. In the 1970's, 1980's and mainly at the end of the 1990's a large number of high-rise buildings appeared.

Based on GIS data of building layers for the years 1972, 1986 and 2003 and a definition of high-rise buildings as buildings with height of 25 meters or more, we found evidence for the assertion that the Tel Aviv urban spatial dynamics are discontinuous in space and non-uniform in time. We found that in each period there is a proportional addition of buildings in each height category, indicating a seemingly random dynamics of high-rise buildings.

In each of the three periods the distribution of all the buildings displays twin peaks, and a moderate tendency for the relative number of low buildings to decrease as function of time (Roth 2009). This can be seen in the histograms for the different years presented in Figure 1.

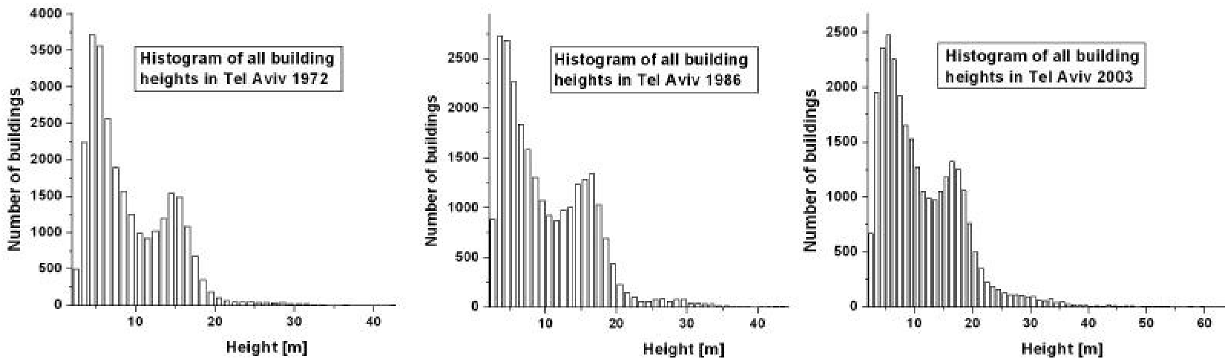

Figure 1**:** Distribution of heights in Tel Aviv 1972, 1986 and 2003 for all the buildings

While the general shape of the height histograms remained unchanged during the three years, there is significant horizontal move representing the transition of Tel Aviv to taller buildings (see Figure 2). The figure consists of three distribution curves of all heights scaled according to frequency axis. The curves display two local maxima and one local minimum.

We studied the spatial dynamics of heights in Tel Aviv based on a grid of cells (Golan 2009). For each cell we calculated the average height of buildings. Figure 3 illustrates this classification according to five natural intervals. Based on a number of clustering tests we found only weak and weakening evidence for clustering of high-rise buildings. Thus, the "average nearest neighbor" clustering measure (Clark et al 1954) displays monotonic increase and weakening of the clustering property over time (ANN=0.31 in 1972, 0.36 in 1986 and 0.39 in 2003). Similar results were obtained based on the Moran Index (Moran 1950), showing a positive tendency to cluster, weakly auto-correlated due to the spatial heterogeneity of the heights (MI=0.03 in 1972, 0.07 in 1986 and 0.04 in 2003).

In conclusion, the evolution of the city is comprised of two interrelated processes: the time evolution of heights and their spatial spread. Both processes do not accord well with Alonso type models.

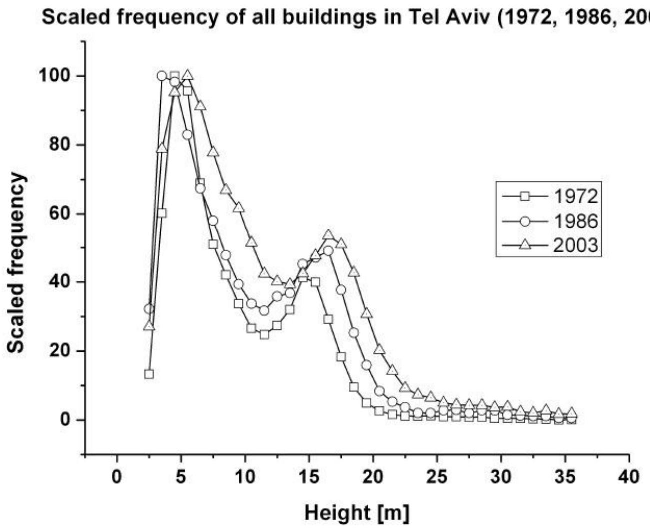

Figure 2**:** Scaled height distribution curves of all heights of buildings in Tel Aviv 1972, 1986, 2003

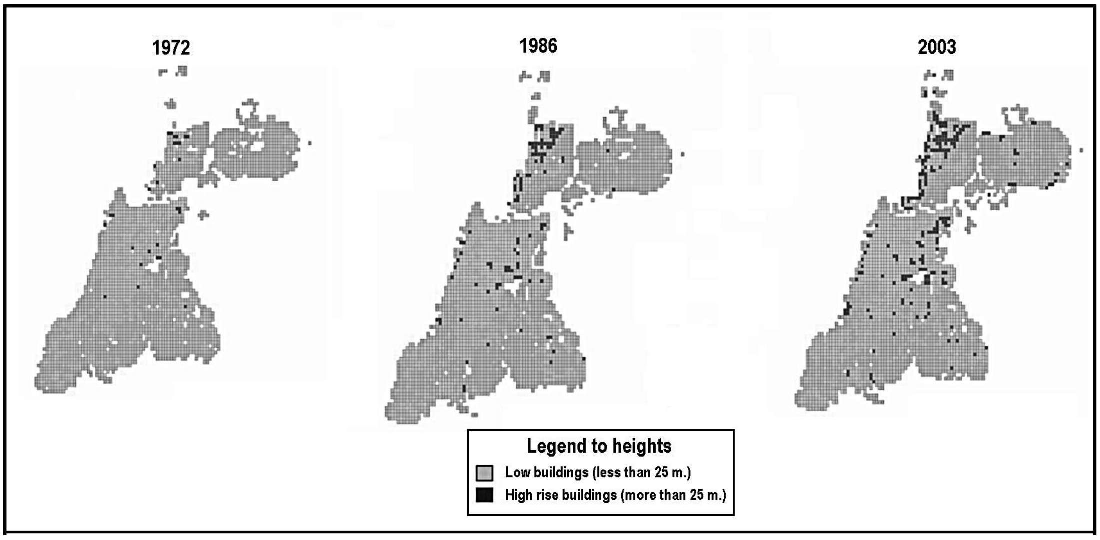

Figure 3**:** The dynamics of heights in Tel Aviv in the years 1972, 1986 and 2003

Developers' behavior, characteristic time and similar cities

At the heart of our approach is a simple conception of land developers' behavior and of the environment within which they function. We assume a linear city. Figure 4 presents the stylized facts. The central business district (CBD) of one city is at X_A. The CBD of another city is at X_B. The boundary between the two cities is at X_L. We begin with the case of one city, city A. The developers' problem is to find an optimal location x* and optimal height h* that leads to profit maximization. The developer's objective function (Czamanski et al 2011) is:

$$MaxFV(t=\tau) = -I(x,h)(1+r)^{\tau} - C(h) + P(x)h$$
$$x,h \qquad (1)$$
$$s.t. \tau = \tau(x,h)$$

Where τ is the characteristic time and accounts for the time from the moment of acquisition of property rights by a developer until the realization of returns. *I(x, h)* represents the land price as a function of location x and building rights expressed as height of buildings, *h*. The discount rate is *r*. The overnight building cost is a function of building height and is expressed as *C*. Finally, *P(x)* is the willingness to pay of buyers at location *x*.

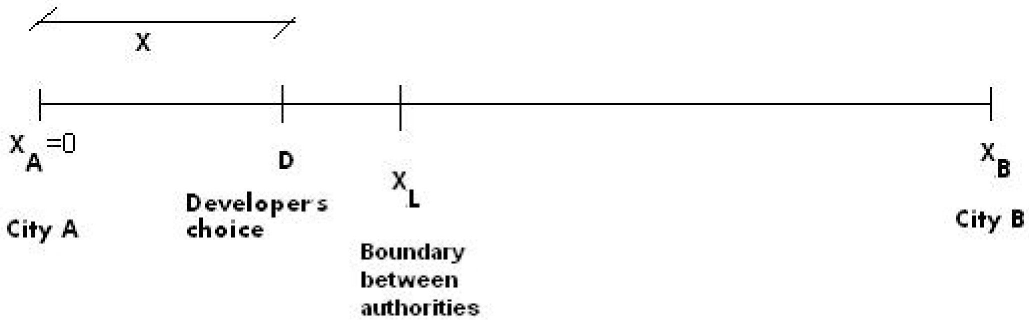

Figure 4**:** The spatial structure of linear cities

Analyzing the first order conditions for the optimal location and height in the single city model, Czamanski & Roth (2011) arrived at the following conclusions:

6. Leapfrogging of heights occurs when

$$\frac{\partial h^*}{\partial \tau} > 0 \text{ and } \frac{\partial \tau}{\partial x^*} > 0 \text{ therefore } \frac{\partial h^*}{\partial x^*} = \frac{\partial h^*}{\partial \tau} \cdot \frac{\partial \tau}{\partial x^*} > 0 \qquad (2)$$

7. There are three distinct possibilities for the sign of $\frac{\partial \tau}{\partial x^*}$:

$$\frac{\partial \tau}{\partial x^*} = 0, \ \frac{\partial \tau}{\partial x^*} > 0 \text{ or } \frac{\partial \tau}{\partial x^*} < 0$$

8. If $\frac{\partial \tau}{\partial x^*} = 0$ then in (2) $\frac{\partial h^*}{\partial x^*} = \frac{\partial h^*}{\partial \tau} \cdot 0 = 0$. In this case the optimal height does not depend on the distance from the CBD.

9. If $\frac{\partial \tau}{\partial x^*} > 0$, then the sign of $\frac{\partial h^*}{\partial \tau}$ in (2) is not clear and the condition for a positive derivative that can lead to leapfrogging is a very low interest rate, such as may occur during periods of recession.

10. If $\frac{\partial \tau}{\partial x^*} < 0$ it can be shown that $\frac{\partial h^*}{\partial \tau} > 0$ and therefore $\frac{\partial h^*}{\partial x^*} = \frac{\partial h^*}{\partial \tau} \cdot \frac{\partial \tau}{\partial x^*} < 0$. In this case, h* is a decreasing function of the distance from the CBD. As in the previous case, only when the interest rate is negligible leapfrogging is possible.

The optimal location model analyzes a single developer’s choice and assumes implicitly that she represents an average behavior. In order to test the implications of different developers' behavior, a simple agent-based model was created, simulating land purchasing and development activities in the context of a single city. If all the developers were constrained to choose only profitable locations with low characteristic time, an Alonso type city emerges, as shown in Figure 5 (left side). Green cells represent undeveloped sites. Dark cells represent intensively developed areas.

With the help of the same model we study the repercussions that developers are allowed to speculate, purchasing land parcels with very high characteristic time. They benefit from low land costs that reflect the fact that development will not be allowed easily and it will take place after long waiting times. On the other hand, as more of such locations are being purchased, pressure on the planning authorities to allow development in those marginal sites rises. If flexible planning policies are introduced into the model, the characteristic time can be lowered in zones where several parcels are waiting for development. If this happens, the speculative developers take advantage of a disequilibrium situation and build high rise buildings exploiting the gap between high willingness to pay and cheap land. Later, other developers are attracted to the zone by the lowered characteristic time, but then the gap between costs and revenues shrinks. This kind of situation leads to the creation of sub-centers far from the initial CBD. The speculative developers act as the workhorses leading to the emergence of a new sub-center. Others follow them should they succeed to change the planning policy in that zone. A typical result is shown in figure 5 (right side). In this case several sub-centers, each with Alonso-type structure, emerge.

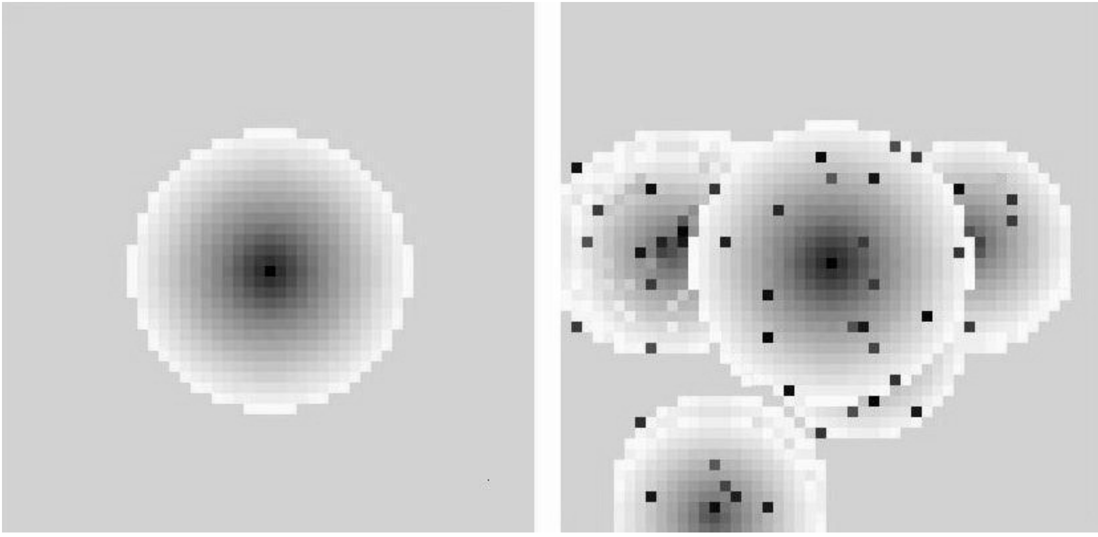

Figure 5: Two-dimensional city model with homogenous developers (left) and speculative behavior allowed (right)

However, the rudimentary model that is the base of this paper is enough to illustrate that even if only an average developer is assumed, interaction between two cities and their respective planning policies are conducive to several cases of leap-frogging, scattered development or sub-centers creation.

In the case of two cities, the CBD of city B is located at X_B. X_L is the administrative boundary between the two municipal areas, A and B (see Figure 4 above). For the present purpose the location of this boundary is insignificant. It is assumed that it was defined as part of an historical, political process. The segment $(X_L - X_A)$ and the segment $(X_B - X_L)$ are not necessarily equal.

In each municipality, the characteristic time is determined by an independent planning authority. We presume that in a Tiebout (1956) style world, each planning authority reflects the preferences of its self-selected residents. The characteristic time in each municipality pertains to its own territory only. As in the single municipality case, τ is a function of the distance from the respective CBD. It is also a function of the intensity of the proposed development. Thus, it is an increasing function of building height. In other words:

$$\tau = \tau(x,h) \qquad \begin{array}{l} \tau^A(x,h) \text{ If } x \in [x_A, x_L] \\ \tau^B(x,h) \text{ If } x \in (x_L, x_B] \end{array} \qquad (3)$$

It is assumed that the developers have precise information about the characteristic time at each location over the segment $[x_A, x_B]$. Various situations may occur, reflecting all the

possible combinations of τ_x^A and τ_x^B (positive, negative or zero functions). Assuming myopic behavior (in the sense that each municipality defines the characteristic time in its respective area of influence independently) or full awareness lead to much more diverse scenarios.
Those scenarios were analyzed elsewhere (Broitman et al 2011) for the case of similar cities and restricted to the developer's behavior under different characteristic times. There the demand side was not included in the model. The conclusions were that myopic assumptions can easily lead to unintended leapfrogging, whereas competition between the cities, including in the case that each city takes into consideration processes in the entire region, can result in intentional leapfrogging or in spatially concentrated development, depending on the policy objectives of the authorities. Additional scenarios of collaboration between authorities with different goals are also feasible.

Dissimilar cities – no competition

We assume that cities A and B are qualitatively different, in terms of population, size, purchase power, etc. A is assumed to be a developed city, with high population (at least one order of magnitude greater than B's population), and consequently offering diverse urban economic, social and cultural amenities (employment, manufacturing and business as well as consumer facilities and educational options). B is assumed to be a small city, much less populated than A and offering a narrow spectrum of urban amenities, but maybe offering better country-side amenities than A (open spaces, less agglomeration, etc.). Furthermore, it is assumed that A and B are located at a commuting distance, meaning that it is possible to live in B and work and/or consume cultural products at A.

From a consumer's point of view, the willingness to pay for a house in this linear model is mainly a function of the distance from the main central business district, as assumed by the mono and multiple-centric urban models (Alonso 1964, Mills 1967, Muth 1969, Wheaton 1974). Since the linear space is bounded by two business districts, each exerts an attraction that operates along the entire $[x_A, x_B]$segment. The strongest attraction forces operate on the edges themselves, being much more powerful in relation to the CBD of A, since A is the bigger city. Along the $[x_A, x_B]$segment they are expected to decrease as the distance from A is increasing, (Osland et al 2005, Osland 2008). B's attraction force causes it to rise eventually as the proximity to the CBD of B increases. The willingness to pay for housing is assumed to be the emerging result of those gravity forces, and its graph is sketched in Figure 6.

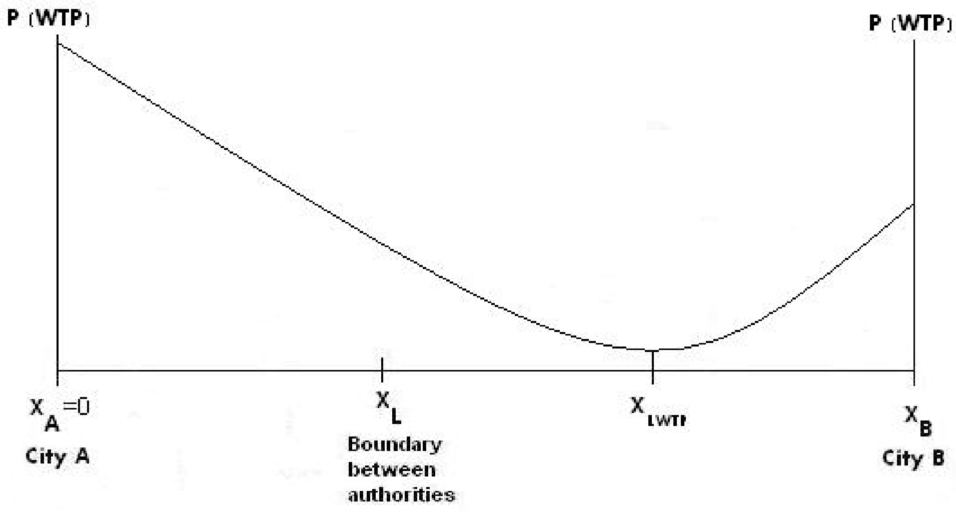

Figure 6: Willingness to pay for housing in the linear model

In order to facilitate the discussion in the following, the developers' objective function defined in (1) is redefined as simpler revenue minus cost function. The first component in the function is $I(x,h)(1+r)^{\tau}$. The initial investment (I) is assumed to be a decreasing function of *x*, and an increasing function of *h*. The characteristic time increases the investment component since it imposes a waiting interest on it. The characteristic time can be an increasing or decreasing function of *x*, and is an increasing function of *h*. The investment cost is augmented if $\tau_x > 0$ and diminishing if $\tau_x < 0$.

The second component $C(h)$ is the overnight cost, an increasing function of the building height ($C_h > 0$). Moreover, its slope tends to increase (its second derivative $C_{hh} > 0$). This is because building a marginal floor should be more expensive than building the previous one (otherwise the result is always an optimal infinite height). The last component is the developers' revenue, namely $P(x) \cdot h$, or the willingness to pay for a house in location *x*, times the number of floors. A developer will build an additional floor until $C(h+1) - C(h) = P(x)$.

Although the initial investment is an increasing function of *h*, it is assumed to be negligible compared with the marginal floor building cost. Therefore, the height parameter itself is simplified to be proportional to the willingness to pay.[1] This simplification allows us to define a developer cost function ($DC(x)$) depending on *x* only. The characteristic time is embedded in it, raising it when $\tau_x > 0$ or diminishing if $\tau_x < 0$.

If a particular fixed height ($h = K$) is assumed for the analysis, the building costs are fixed and can be ignored since they are the same in each location. Using the following substitutions

[1] Another way to consider our simplification is to assume that we are considering the profitability of a single building of a particular height at different locations.

$$- DC(x) = -I(x)(1+r)^{\tau}$$
$$s.t. DC = DC(\tau(x)) \quad (4)$$

$$P(x) \cdot K = WTP(x) \quad (5)$$

The developer profit objective function defined in (1) was simplified as

$$\begin{aligned} & Max \pi = -DC(x) + WTP(x) \\ & x \in [x_A, x_B] \qquad (6) \\ & s.t. DC = DC(\tau(x)) \end{aligned}$$

The new objective function π defined in (6) can be visualized as the difference between the developer's cost function and the willingness to pay along the $[x_A, x_B]$ segment as in figure 7.

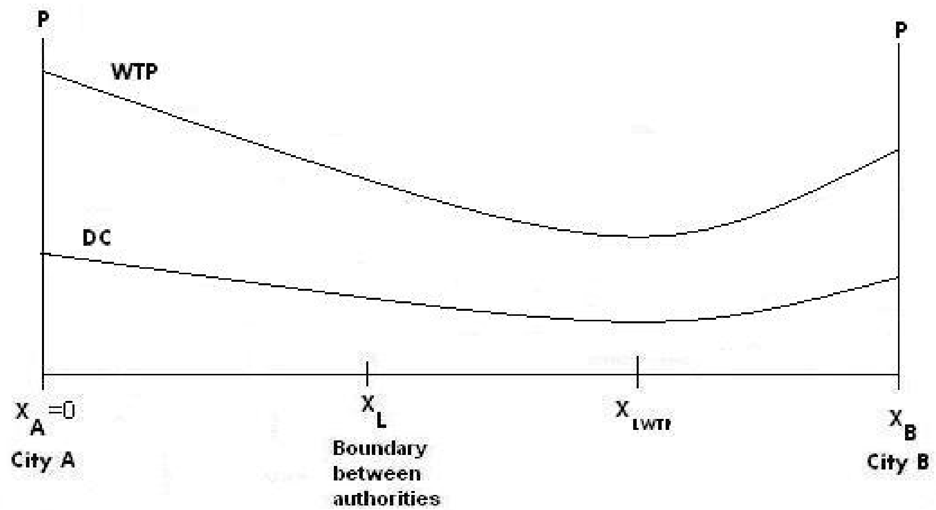

Figure 7: Willingness to pay and developer costs in the linear model

The assumption that $\tau_x^A = 0$ and $\tau_x^B = 0$ means that planning policies are place independent in the case of both cities. In other words, in each city characteristic time does not depend on location, nor is it dependent on the optimal height of proposed building projects. The developer's decision concerning where and at what intensity to build is not influenced by characteristic time imposed by the municipalities (since it is the same at each location). Clearly, in this case, the maximization problem is solved at CBD A, because the WTP is greatest.

In this case the regional development will follow the pattern depicted in Figure 8: First, all the available sites will be developed from CBD A outwards, till x_1 (arrow 1). In a second phase, the segments $[x_1, x_{LWTP}]$ and $[x_{LWTP}, x_B]$ will be developed intermittently according to the slope of the WTP function (following arrows 2 and 3), finishing in x_{LWTP} only when running out of place.

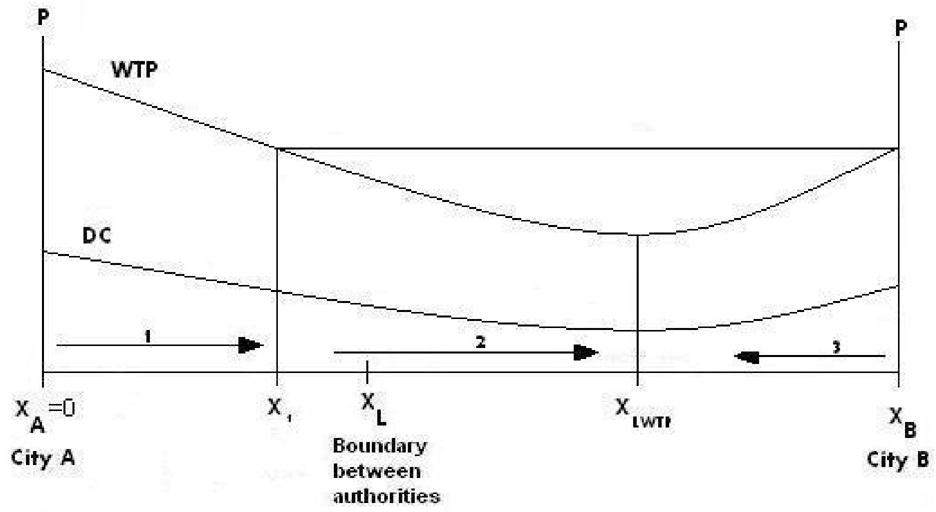

Figure 8**:** Willingness to pay and constant characteristic scenario

A different scenario arises when one municipality implements a constant characteristic time policy, and the other implements either an increasing or decreasing characteristic time as function of the distance from the CBD. If the developed city A wishes to avoid leapfrogging (and therefore in its territory $\tau_x^A > 0$), while in city B area $\tau_x^B = 0$; the result may be an undeveloped gap (as segment $[x_1, x_L]$ in figure 9). This is because A's policy increases the developer's costs, but only until A's administrative boundary (x_L). In this case, A's myopic behavior can lead to an outcome opposite to that intended originally - Scattered development arises beyond its municipal boundary.

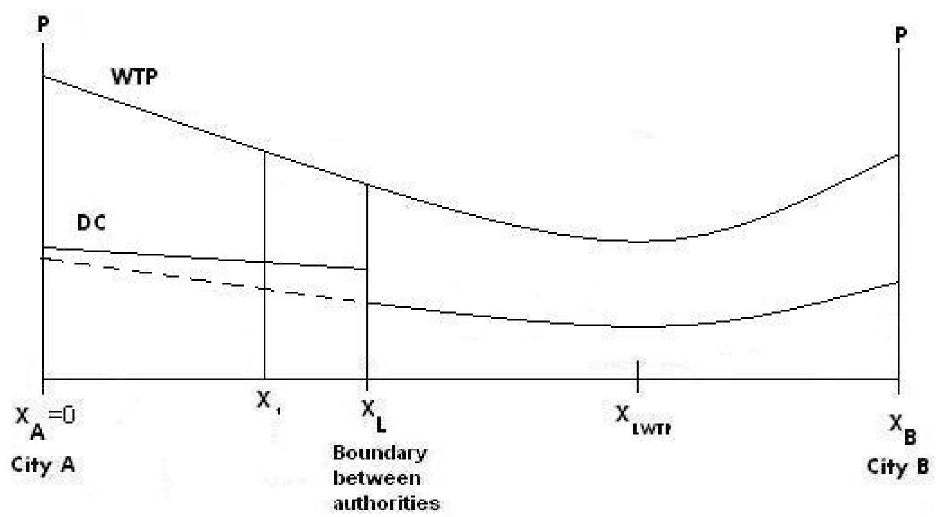

Figure 9**:** No competition, $\tau_x^A > 0$ and $\tau_x^B = 0$

If A implements a policy aimed to spread its development, for reason such as excessive agglomeration in its CBD, then $\tau_x^A < 0$, and the results will be according to A's policy. However, this policy can lead to an unintended over-development of B. If developers' profit in A's CBD diminishes enough, the highest profits can be achieved in B's CBD. Again, myopic behavior can lead to unexpected results, unless the policy was coordinated between both municipalities and the outcome is welcomed by both. Figure 10 describes this scenario.

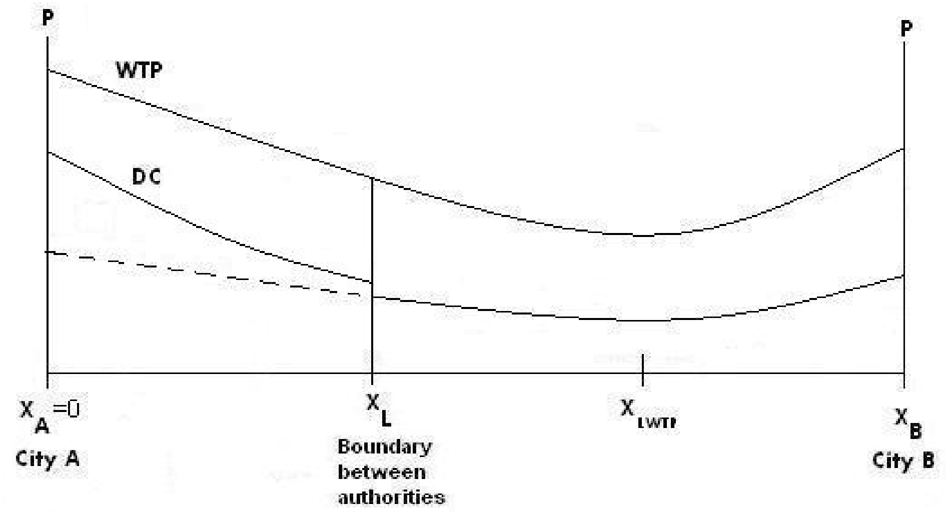

Figure 10**:** No competition, $\tau_x^A < 0$ and $\tau_x^B = 0$

Inversely, an increasing characteristic time implemented by the smaller city B, may lead to a concentrated development in A's territory. If $\tau_x^B > 0$ and no specific policy is implemented by A ($\tau_x^A = 0$), development can be severely restrained on $[x_L, x_B]$, as can be seen in figure 11. On the other hand, if the policy implemented by city B is the opposite ($\tau_x^B < 0$) the result is an incentive to leapfrogging development in segment $[x_L, x_B]$, as depicted in figure 12.

Since the willingness to pay near the big city is greater than in any other place in the linear model, increasing development costs in B's territory near the administrative border will restrain development to segment $[x_A, x_L]$ (Figure 11). On the other hand, increasing development costs in B's center may be an incentive to develop the border zone in B's area. Whether it is a desirable outcome or not, depends on the big city development policies and goals. Again, a myopic behavior (in this case of city B) can lead to unexpected outcomes on the other side.

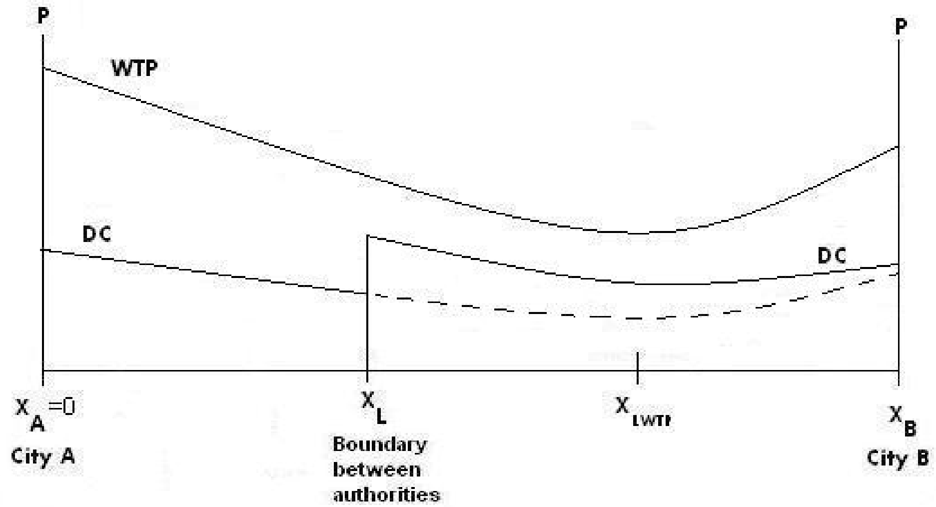

Figure 11: No competition, $\tau_x^B > 0$ and $\tau_x^A = 0$

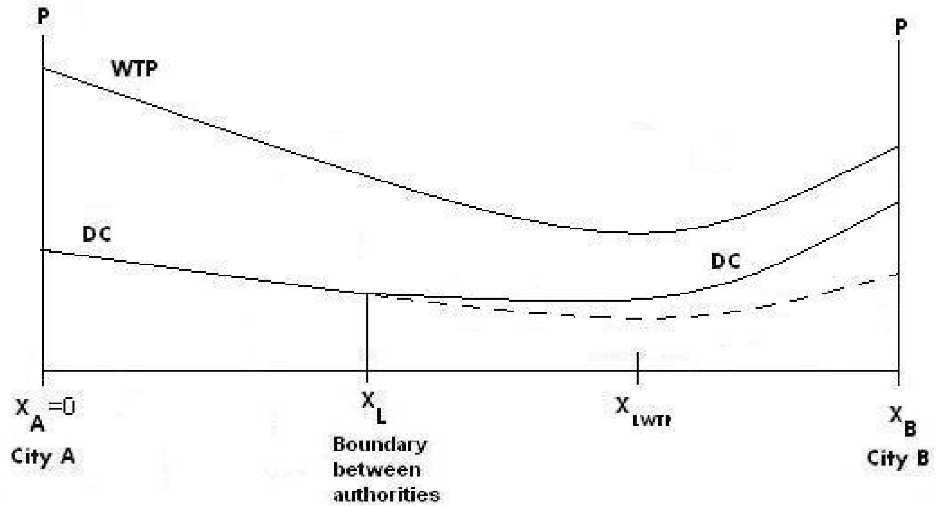

Figure 12: No competition, $\tau_x^B < 0$ and $\tau_x^A = 0$

Competition among dissimilar cities

In this section we assume that the qualitatively different two cities are in rivalry. If the development policies of the municipalities are similar, they will compete in order to pursue their goals. If an urban concentration policy is defined by both municipalities, then both $\tau_x^A > 0$ in $[x_A, x_L]$ and $\tau_x^B > 0$ in$[x_L, x_B]$, in order to discourage development far from the respective CBDs, raising costs as the distance increases. In this case the respective cost and WTP curves will look as in Figure 13. Development is profitable mainly in areas near the big city business center, and, as a second option, in areas near the small city CBD, whether development in the hinterland in strongly discouraged.

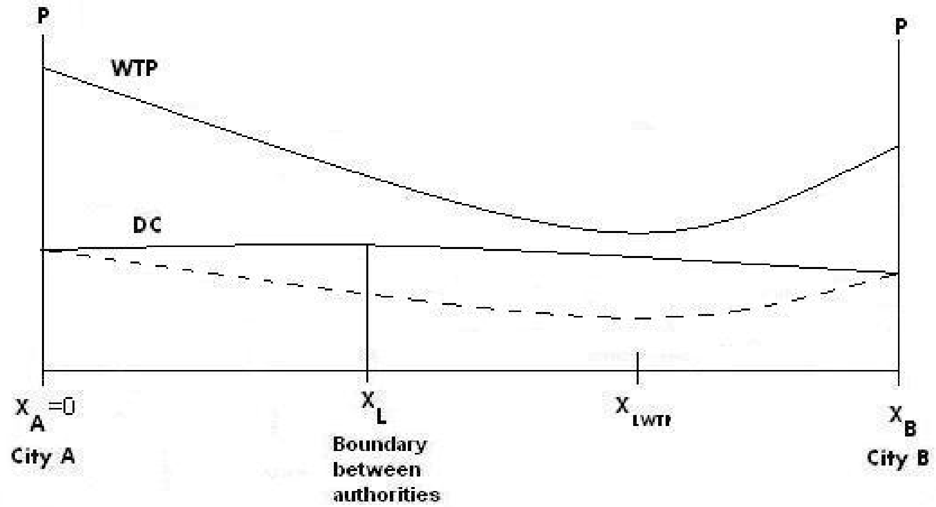

Figure 13: Rival cities, $\tau_x^A > 0$ and $\tau_x^B > 0$

If we assume that other policies are adopted by both municipalities, for example, spreading the development far from the respective CBDs, then both $\tau_x^A < 0$ in $[x_A, x_L]$ and $\tau_x^B < 0$ in $[x_L, x_B]$. The effects of decreasing characteristic time with the distance from the center on the cost function are twofold: Raising the cost near the CBDs and lowering it in the hinterland, as seen in Figure 14.

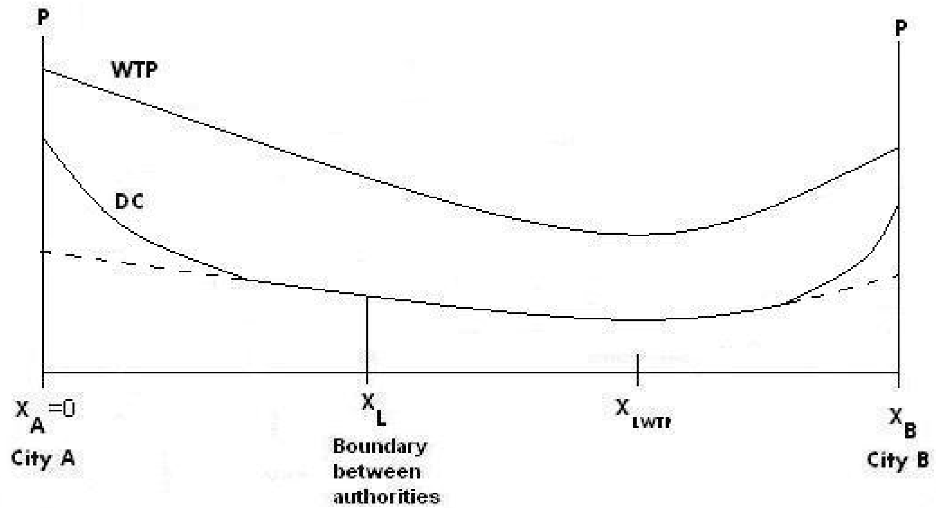

Figure 14**:** Rival cities, $\tau_x^A < 0$ and $\tau_x^B < 0$

Though the development spreading goal can be achieved from the point of view of both municipalities, potential conflicts still can arise due to the mismatch between the administrative boundary and the point where the willingness to pay is lowest (in other words, due to the mismatch between the economic attraction of city A and the territorial arrangements). Development in the segment$[x_L, x_{LWTP}]$, despite being welcomed by both municipalities, contributes with city B (via property taxes, for example) much more than with city A. In that segment, a new building is constructed because of A's attraction force, but B benefits from the outcome (assuming that both sees leapfrogging as a positive result).

If the cities development policies differ, while assuming that both municipalities are aware of the tendencies and processes occurring in the entire $[x_A, x_B]$segment, different conflicts can occur, depending on the location of the administrative boundary, the relative economic strength of the cities, and the extent of cooperation or competition between them.

If the big city A is willing to spread its development outwards, it can implement a characteristic time that encourage developers to build far from the center ($\tau_x^A < 0$), but only in segment $[x_A, x_L]$. At the same time, city B is willing to conserve its open space and therefore implements a restrictive policy ($\tau_x^B > 0$) in$[x_L, x_B]$ affecting the cost function, as can be seen in Figure 15.

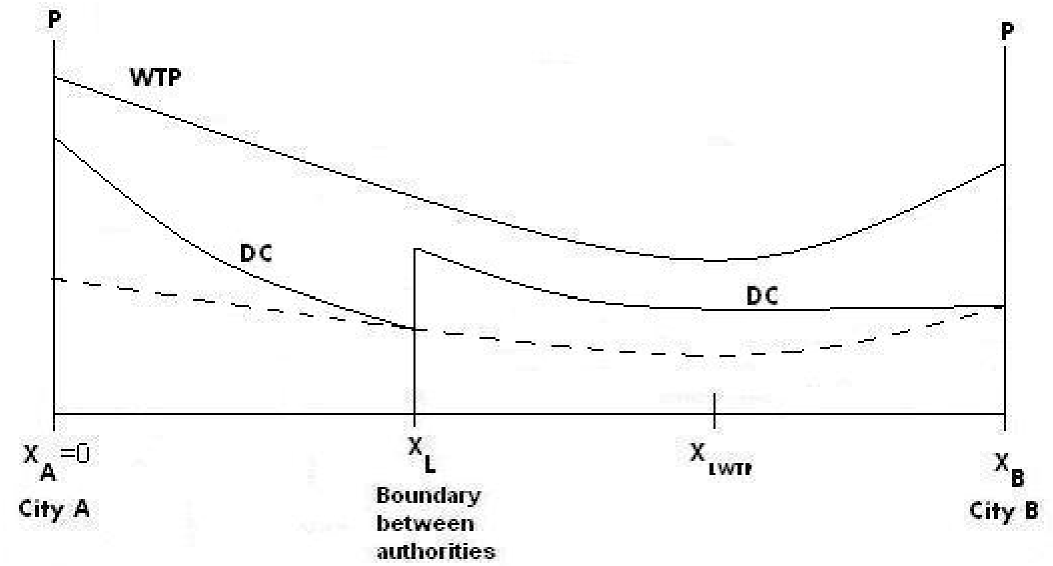

Figure 15**:** Rival cities, $\tau_x^A < 0$ and $\tau_x^B > 0$

Under these conditions, the A border side (left tox_L) is expected to develop faster and create a leapfrogging pattern in A's territory. Across the border and till city's B edge, there are expected to be no buildings. City A is able to use all its territory in order to pursue its goals, but on the other hand (if x_L is too closer to A) this area might be not enough for this. City B may prefer to see most of $[x_A, x_B]$as open space, but is able to exert influence only on segment$[x_L, x_B]$. An alternative interpretation may be that both cities coordinate their policies in order to take advantage of the entire area, each one maximizing its utility according to its preferences. The problem with this interpretation is that city A is not only achieving its goals, it is free-riding on B's willingness to maintain open-spaces. Dwellers on the newly developed neighborhoods near A's boundary will enjoy plenty open spaces for free, whereas city B is loosing (readily) potential income. This opportunity cost of city B, can lead to claims from city A.

Reversing the scenario, if the big city A is willing to concentrate its development near its business center, it can implement a characteristic time that encourage developers to build as near as possible from the center ($\tau_x^A > 0$), but only in its own administrative area, segment $[x_A, x_L]$. City B is allowing development far from the business center in its area, and implements a permissive policy ($\tau_x^B < 0$) in $[x_L, x_B]$. The resulting cost function is depicted in Figure 16.

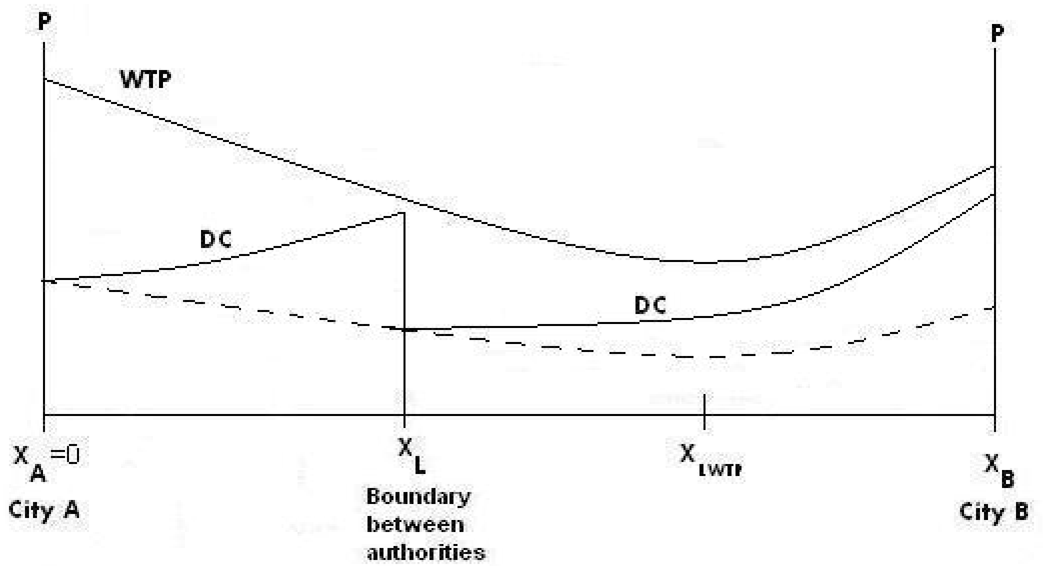

Figure 16**:** Rival cities, $\tau_x^A > 0$ and $\tau_x^B < 0$

In this scenario, the fast developing areas will be A's central business district, and near the border in B's area. The result is an unintended leapfrogging pattern from the point of view of city A. The small city is taking advantage of the fact that the big city attraction is felt far away from its administrative border and is getting revenues from urban development that is located in its area due to the proximity to the big city A. City A is constraining its own spatial development in order to keep enough open spaces at its edge, but it is forced to witness fast and unintended development on the border's other side. City B is not likely to give up its revenues from property taxes and population growth for nothing. One possible solution for the conflict is compensation from city A to B, in exchange to avoiding some development in B's area. Such compensation should be equal to the opportunity cost lost by B when cancelling a welcome urban development.

Conclusions

A simple developer's behavior model, in the context of a single city within a linear space, is able to explain leapfrogging and scattered development as a consequence of spatial variation in characteristic time, especially in times that interest rates are low or negligible (Czamanski et al 2011).

If two cities are sited at opposite edges of a linear space, the same situation can arise, but additional factors play an important role and need to be considered. In this case, each city defines its own development policies that are reflected in different characteristic time functions in each territory.

Assuming that both cities are qualitatively different, a developed city with a large population and diverse economic, social and cultural amenities and a small city at the opposite edge, additional forces and interactions between them emerge. In this scenario, mutual attraction forces will operate along the entire region, interacting with the political boundary between them, which not necessarily reflects the gravity influences shaped by the market forces.

If each city is interested only in what happens on its side of the boundary, a behavior we term "myopic" in this paper, leapfrogging patterns can easily develop. Even full awareness, in the sense that each city takes into consideration processes in the entire region, can result in intentional leapfrogging created by competition between the cities. However, in this case, spatially concentrated development is possible, depending on the policy objectives of the authorities. Additional scenarios of collaboration between authorities with different goals are also feasible.

The model simulates processes occurring during a phase when both cities are growing, and the land and residential markets are not in equilibrium. In the long run an equilibrium stage where profitability is the same everywhere will eventually be reached, but our interest is focused on the long period (years or decades) in between. In such disequilibrium situations, local maxima in profitability are possible, for example in some of the scenarios depicted before. Those local maxima can be intentionally or unintentionally created by cities authorities, emerging from non-monotonic time incidences on development along their territories. Since profitability is highly influenced by time incidence, developer's location decisions can be very different from results expected by models assuming monotonic profitability decline from the CBD.

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4.3. Paper #3

Polycentric urban dynamics - heterogeneous developers under certain planning restrictions

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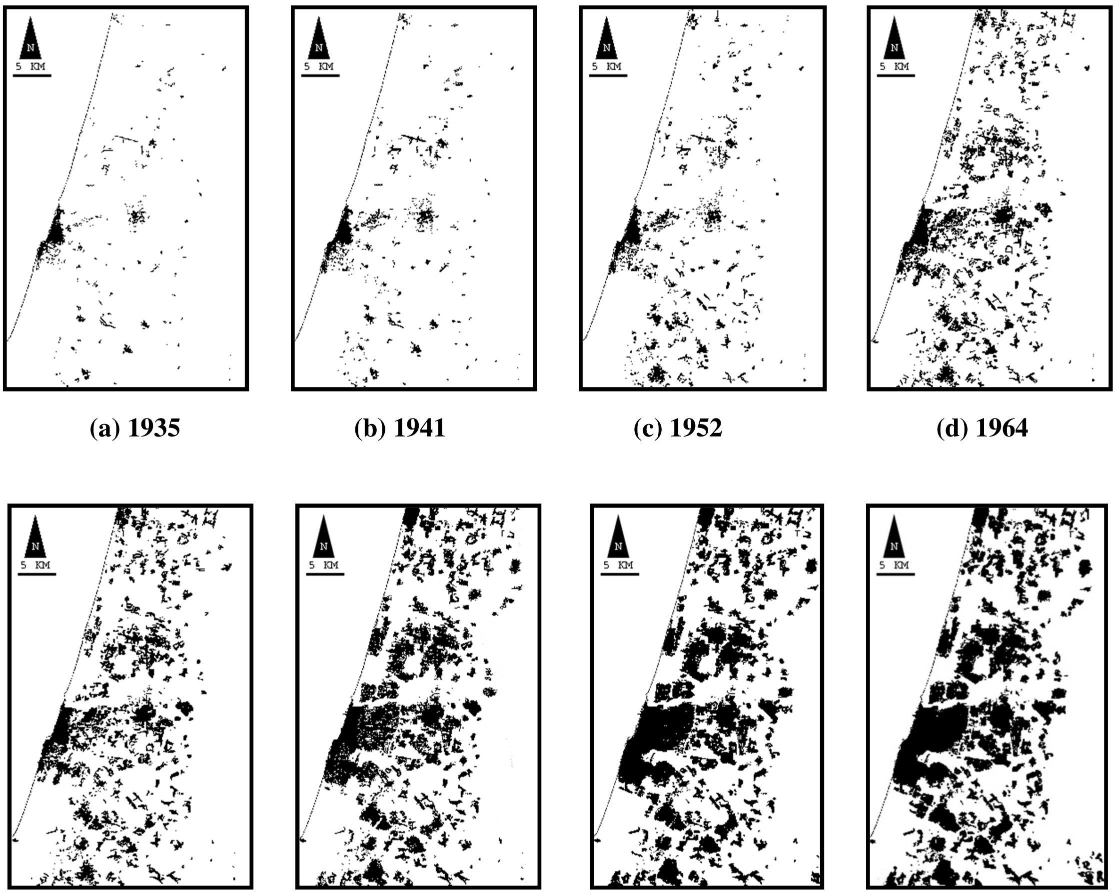
Abstract

The paper is concerned with the formation of polycentric cities. The model we introduce includes two types of developers and planning authorities. Developers' characteristics, such as scale of operations, availability of own-capital and time preferences lead to various decisions concerning the choice of location and development investment. They are influenced by planners' decisions concerning developable locations. We present a cellular automaton model that simulates the interaction of various types of developers and planning authorities. We demonstrate that the joint dynamics of decisions by impatient, low scale developers, with others who are willing to wait a long time to realize returns on their investment can lead to the creation of new urban sub-centers.

Introduction

Classical models of urban spatial structure (Alonso 1964, Mills 1967, Muth 1969) depict cities as mono-centric. They view real cities at a crude resolution only. To this end they utilize average densities (Alperovich & Deutsch 2000). In these models people and activities compete for space and locations in terms of proximity to a single city center. The competition leads to a monotonically declining land rents and density from the CBD outwards (Fujita 1989). Such models are hard pressed to explain the formation of modern cities with the typical polycentric structure.

Recent research concerned with urban spatial dynamics suggests that discontinuity in space and non-uniformity in time are a prominent characteristic of modern urban development (Benguigui et al 2001a, 2001b, 2004a, 2004b, 2006). Thus for example, the footprint of the built area in the Tel Aviv conurbation displays discontinuity that appears as a result of apparent leapfrogging (see Figure 1).



(a) 1935 (b) 1941 (c) 1952 (d) 1964

(e) 1974 (f) 1985 (g) 1993 (h) 2000

Figure 1: The temporal evolution of Tel-Aviv's footprint

Furthermore, the evolution of high-rise buildings represents evidence contrary to the mono-centric paradigm. There is some evidence of that clustering of high-rise buildings over time is weakening (Golan 2009). Quantitative measures indicate that no single urban center of attraction is present in the city (Czamanski and Roth, 2011). Moreover, new high-rise building clusters seem to arise over time in zones previously not intensively developed (Golan 2009).

In an effort to explain the apparent discontinuities in the spatial evolution of built areas, we argue that the polycentric structure results from the behavior of developers that incorporate the preferences of consumers (Henderson et al 2008), together with measures taken by planning authorities. The planning actions are comprised of land-use plans intended to prevent unwanted urban development in areas reserved for nature, parks, recreation and agriculture (Furst et al 2010). The effectiveness of land-use plans is related to the ability of planning boards to withstand the pressure of developers to convert land that is not intended for development and was purchased by developers at a low market price into high proceed developable land (Lai et al 2008). While the ability of developers to influence planning boards and to obtain planning variances varies among countries, it is a universal phenomenon. As we shall demonstrate in this paper the resistance of planning boards is directly responsible for sprawl in the form of leapfrogging.

The overall purpose of this paper is to incorporate planning decisions into an agent-based simulation model that yields realistic urban spatial structures. It is our claim that the combined effect of urban planning policies and regulations and the choices of developers searching for real estate projects can explain much of the urban spatial-temporal evolution. Firm characteristics, and in particular the time impatience of land developers, interacts with time-related municipal development strategies and in turn, affects the urban spatial structure dynamics.

The rest of this paper consists of 3 more sections. The next section contains a description of our model. The following section present results of model simulations. The last section presents discussion of our results and suggestions for future research.

Model description

We present an agent-based model with two main types of agents. Planning authority sets rules concerning the location and intensity of developable land. We assume that planning building restrictions grow with distance from the CBD. These restrictions are expressed as a monotonically increasing function of the time required for obtaining construction permits as the distance from the CBD increases. From the developers' point of view this is the time spanning between acquisition of property rights and the realization of returns. We define it as the characteristic time of a given location. Developers are the second type of agents. They select preferred locations for buildings and the intensity, or height, of buildings. We define two types of real estate developers. The first type is an impatient developer, characterized by small scale operations resulting in low and medium height buildings and preference for immediate returns on investment, henceforth "small" developers. The second type is patient developer, characterized by financial capabilities, ability to wait long periods in order to maximize returns on investment and large scale of development operations (high rise buildings), henceforth "big" developers.

As we shall illustrated in the following the presence of one homogenous group of "small" developers results in an Alonso-type mono-centric city. Most cities, however, display a polycentric structure (Czamanski and Roth, 2011). In our model we generate polycentric structure by including a mix of small developers and large, patient, developers. As long as land is available for development within a radius with characteristic time that is below or equal to the developers' time impatience, building will proceed and the competition for accessibility will generate an Alonso-type city. This circular-shaped mono-centric city has a radius directly related to the characteristic time function imposed by the planning authorities. As available land in the mono-centric city is exhausted, pent-up demand will cause willingness-to-pay to rise. Some of the "small" developers with a preference for "immediate" returns on investments will leave the sector of land development and turn to other activities. A period of building stagnation without significant construction activity will follow.

However, some "large" developers, patient enough to wait for long-term returns, will speculate and purchase low priced land for future development. This land is in areas with high characteristic time. They will hold the land until the characteristic time will elapse and building will be possible. By waiting it out the "big" developers will achieve a return on investment that is higher than in the core of the city. Also, they will purchase old buildings within the pale of the CBD that can be demolished and thus make land available for high-rise modern structures. Due to historic preservation constraints, limited and outdated urban infrastructure and opposition from neighbors the characteristic time of these sites is high.

When many parcels of speculatively bought land are concentrated in a particular region, the planning authorities acknowledge that the region is being urbanized despite the high characteristic times imposed in it, and with some probability, reduce the characteristic time around this new development pole. "Small" developers with a preference for "immediate" returns on investments are attracted to the region and start building as well. A new Alonso-type urban center will be created.

The timing of the peaks and troughs in construction activities is a function of size and rate of change in the characteristic time. The number, size and speed of construction of sub-centers depend on the relative number of the two types of developers and the city development policies regarding the characteristic time. "Big" developers get out of development business and get back, into both speculative and construction activities, following the external economic cycles. There may be a delay and each type of activity can depend on different characteristic of the cycle.

Our spatial, agent-based simulation model displays the city spatial configuration in each time step. The city is defined as a square grid of cells, each of which represents a single parcel of land. The cells' status in any given time step is characterized by several attributes:

<u>Characteristic time</u>: The time delay imposed on each specific cell by city authorities on potential developers from the time that property rights are purchased and until the project construction and revenue realizations. This attribute is a function of location. Also, characteristic time increases with height.

<u>Cell use status</u>: One of the following three statuses is possible – Available (not developed), purchased (waiting for the characteristic time elapsing, and therefore, not developed yet) or developed (an occupied cell with a building standing in it). Status can change over time.

<u>Height</u>: Zero if non-built, otherwise the height of the constructed building.

In the initial time moment the city is just a CBD represented by a single building located in one cell in the center of the grid. All other cells are available for development. The initial distribution of the characteristic time reflects municipality's policy and increases monotonically according to its distance from the CBD.

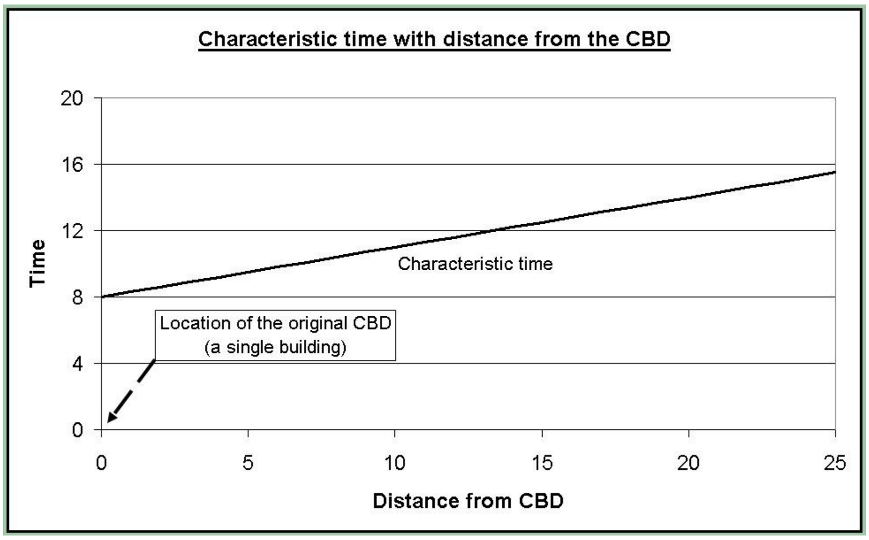


Figure 2: City's transect at the initial stage - single CBD and increasing characteristic time

The attractiveness of a location is expressed by the willingness to pay (WTP) for a dwelling unit in that site by residents. The willingness to pay declines from the city's center and determines the revenues and profits of developers and therefore the price of land. Both parameters (WTP and land price) are assumed to reach local maxima in high rise buildings, proportionally to their heights, decaying linearly as the distance from them increases. In the initial stage both values are defined from the single CBD outwards in all directions. In this case the willingness to pay and the land value local maxima are absolute maximums as well at the CBD.

There are a predefined number of real estate entrepreneurs that are active in the city: N "small" developers and M "big" developers. "Small" developers are characterized by a fixed upper time T. They seek to maximize profits in construction projects only if they could be finished in a time horizon of T years. From their viewpoint, a suitable parcel is one in which $\tau < T$ (τ is the characteristic time). The characteristic time is a function of location and height:

$$\tau(x,h) = \tau_L(x) + \tau_H(h)$$

Although the $\tau_L(x)$ term is defined by the city planners, the $\tau_H(h)$ term is an endogenous decision of the developer and is proportional to the project height.

The "small" developers' algorithm of the choice of location and height of buildings is the following:

1- Choose randomly one cell of all vacant cells for which $\tau < T$
2- According to the WTP and the land cost, calculate the minimal height $h_{\min}$ required in order to make some profit
3- Estimate maximal h, for which $\tau(x,h) = \tau_L(x) + \tau_H(h) = T$; if $h \geq h_{\min}$ purchase the land, wait time T and develop the project of the height h.

The city development policy is to allow development on cells satisfying $\tau < T$. Therefore, the "small" developer's strategy is risk-free. They are assured that any project proposal defined by their algorithm will be approved and finalized in a period T.

City planners aim at supplying growing city population with housing. They monitor construction activity in the city by estimating an average "construction index" over a predetermined period of time. Thus, the construction index is used as a proxy for population growth. If the building index surpasses the threshold, housing supply is considered high enough. If it is falls below the threshold, administrative measures are taken to encourage new development. The planners react to the demand by the "big" developers to permit construction on parcels with high characteristic time.

The "big" developer takes a different approach from the "small" one. In early city development stages, when the city's core (i.e. sites where $\tau < T$) is still not fully developed, she will choose sites there, but since she is not constrained by time, its projects will be considerably more intensive (i.e. high-rise buildings) than those of its "small" counterparts.

Once sites where $\tau < T$ become unavailable, the "big" developer has two risky choices. One possibility is to purchase a low building in the city core, and replace it by a high-rise building. Due to limited and outdated urban infrastructure and opposition from neighbors the characteristic time of these sites is large. The other choice is to speculate and buy land for future construction and future returns in the periphery of the city. The second choice is "speculation" because it is against the declared city policy. In order to obtain construction approval, the developer gambles for a future change in the municipality's policies.

The policy change can become a reality when the city core is fully developed and the construction index falls below the threshold. A stagnation situation arises during which "small" developers are inactive, since sites with $\tau < T$ are unavailable. There are some sites in the city periphery that "big" developers are willing to build, but are prevented to do so by the municipality. The simpler palliative solution from the city viewpoint is to give up and approve some of the development sites in the periphery. This administrative action may push the building index above the threshold but only for a short period of time.

"Big" developers' speculative behavior increases when sites in the periphery receive building approvals. They are attracted by those peripheral sites since they have justified expectations to receive building approvals and, indeed, if the building index falls again below the threshold they will be able to develop closer sites. However, financial capabilities of the "big" developer are limited. There is an upper bound on the quantity of sites that can be held in waiting status.

These dynamics lead to small clusters of high-rise buildings that emerge in peripheral areas. When such clusters become concentrated enough, city planners realize that the slow high-rise building permissions created the seed of a new urban sub-center, and that the specific peripheral zone will become urbanized. The municipality then relaxes the characteristic time constraints in that zone, defining its lowest level in the new cluster, and gradually increasing it outwards. The exact characteristic time function reflects the building boost that city planners are willing to allow. A smoothly increasing function will transform a wider area available for development than a sharp one. In any case, a large set of new locations where $\tau < T$ is created, and therefore new opportunities both for "big" and "small" developers arise. Both devote themselves to the new sub-center development, giving rise to a construction boost that pushes the construction index far above the threshold. The increased activity continues until the new sub-center is fully developed, followed by a new stagnation period, when the whole process is expected to happen again.

The main model elements are described in the following list:

1 – Economic parameters: Willingness to pay, land price and their rate of decay with distance. These parameters are kept fixed in all the scenarios described hereafter.
2 – Developers composition (number of "small" and "big" developers active in the city). Different developers' composition will lead to different spatial results.
3 – City planners monitoring and policy tools: Building index over time, and policy setting parameters. Most of these parameters are kept fixed in all the analyzed scenarios. The only one which is changed is the size of the area allowed for development when a new peripheral area is urbanized.

The following table summarizes the model's parameters:

Parameter	Comment	Value	Unit
Willingness to pay	Represents the WTP for a dwelling unit close to an existing single-story building (fixed in all scenarios).	4000	$
Rate of decay of the WTP	The linear rate of decay of the WTP with distance (fixed in all scenarios)	0.5	No unit
Land price	Represents the land price for a parcel close to an existing single-story building (fixed in all scenarios)	4000	$
Rate of decay of the land price	The linear rate of decay of the land price with distance (fixed in all scenarios).	1	No unit
Distance	The distance between two cells. Each cell represents a standardized square building lot of 100 m. X 100 m.	--	Pixels
Time	All time units in the system (characteristic time of each cell, model running time, etc.) are defined in terms of system ticks. Each tick represents a year.	--	Ticks
Number of "small" developers	Value changes according to scenario	--	Number of developers
Number of "big" developers	Value changes according to scenario	--	Number of developers
Radius of the area allowed for new	Value changes according to scenario	--	Pixels

urbanization			

Table 1: Model's parameters

Results

Most model parameters are kept fixed during all the scenarios runs. Only a selected group of parameters are changed in order to allow sensitivity tests. Those key parameters are the relative number of "small" and "big" developers and the area defined for a new urbanization pole once the authorities decide to allow development in a previously open peri-urban space. Within each scenario each key parameter is specified.
In all the following simulations a high characteristic time function is assumed.

First scenario: Homogeneous developers

In the presence of a homogenous group of "small" developers the cityscape resembles an Alonso-type city. The city size and its height distributions depend on the development policy implemented by planning authorities. Assuming a single development strategy (willingness to concentrate urban development around the existing city core and prevent sprawl) three different policy settings are explored: A constrictive setting characterized by high characteristic times, a more relax setting with medium ones and an expansive policy using low characteristic times. In all the three cases the characteristic time functions increases monotonically from the CBD outwards. The following table defines the key parameters of this scenario:

Parameter	Value
Number of "small" developers	10
Number of "big" developers	0
Radius of the area allowed for new urbanization	10 pixels

Table 2: First scenario key parameters

Figure 3 illustrates the final result of each of those policy settings viewed from above. Higher characteristic time results in smaller available for development area (left image) whereas lower ones expand the suitable land range. Figure 4 describes the height transects of these characteristic time settings.

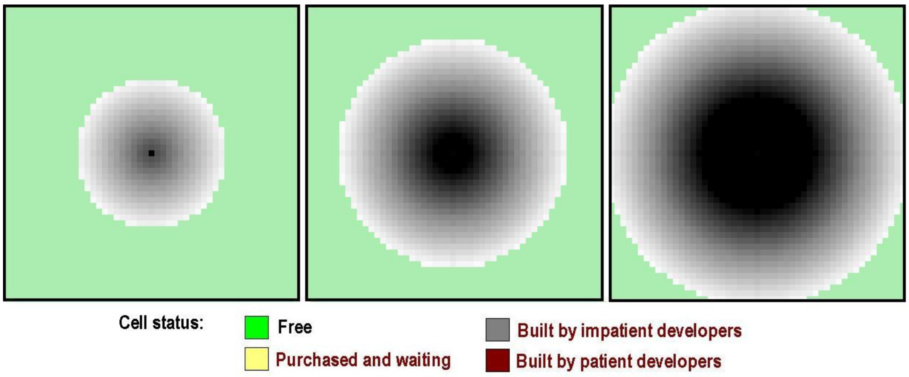


Figure 3: Upper view of a city with homogeneous "small" developers. From left to right, high, medium and low characteristic time functions

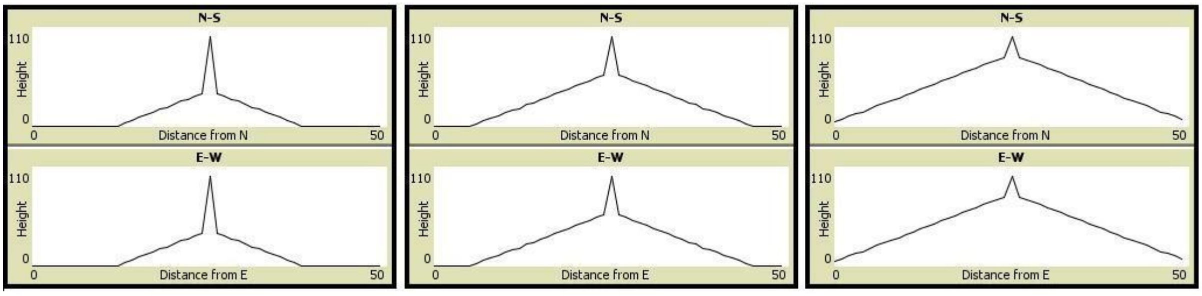


Figure 4: Transects of a city with homogeneous "small" developers. From left to right, high, medium and low characteristic time functions

The overall building activity in each of the cases is characterized by a single construction burst, maintained until each available development is occupied. Since low characteristic time implies larger spaces available for development and higher buildings in any given site, a low characteristic time function will result in a steeper, wider and long-last cycle of construction activity. The following diagram indicates the accumulative construction activity in a mono-centric city according to the different policy settings.

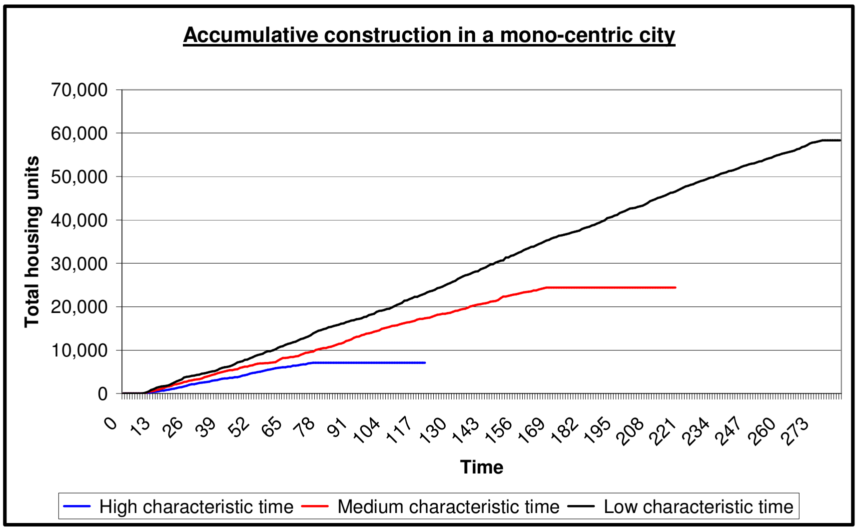


Figure 5: Construction activity in a city with homogeneous "small" developers.

In the presence of a homogenous group of "big" developers the cityscape will show a scattered spatial structure where only high-rise buildings are present and urban centers are hard to recognize. Since small clusters of high-rise buildings are created elsewhere ("small" developers do not exist in this scenario), in the long run the municipality identifies seeds of new urbanizations dispersed randomly in the space, and relaxes the characteristic time virtually everywhere. As a result, "big" developers are able to build in any place, and a continuum of high-rise buildings emerge.

Second scenario: Heterogeneous developers (10 "small" vs. 1 "big")

When a heterogeneous group of developers is allowed, the results are radically different. Even the introduction of a single "big" developer radically changes the way the system evolve. A typical simulation, in which 10 "small" and a single "big" developer participate, starts with a mono-centric city, as long as low characteristic time parcels are available. The following table defines the key parameters of this scenario:

Parameter	Value
Number of "small" developers	10
Number of "big" developers	1
Radius of the area allowed for new urbanization	10 pixels

Table 3: Second scenario key parameters

Figure 6 (left frame) shows the central city configuration, when red cells represent sites developed by big-scale developers, and yellow sites represents sites purchased by them but in waiting status. As time passes, the building index, which experienced a boost during the central city development, decreases below the threshold acceptable for the municipality (20 dwelling units in 20 time units) as showed in figure 7. In response, waiting parcels with high characteristic time are allowed to be developed. But those developed sites in the edge of the mono-centric city become development pole created by "big" developers, and the municipality further response is to relax the characteristic time around the site. "Small" developers can turn back into the real estate market since new opportunities are now available, and indeed, a new sub-center arises around the site (Figure 6, center). Later, another aggregation of high-rise buildings in the northern periphery of the city leads to the creation of a new sub-center, at a greater distance than the previous one (Figure 6, right picture).

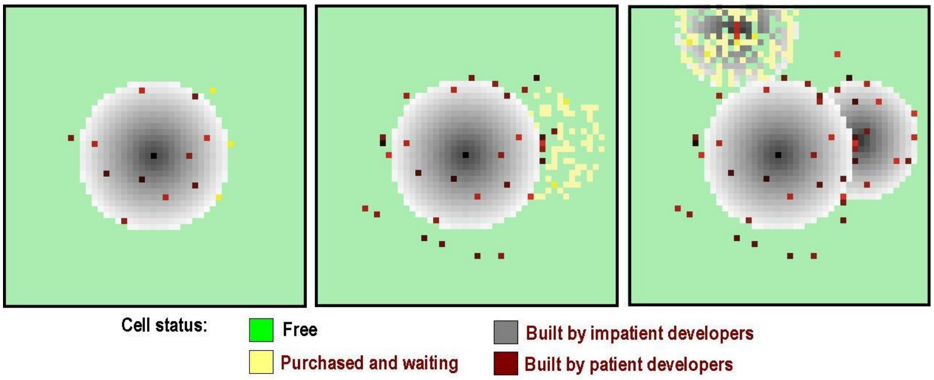


Figure 6: Polycentric city development

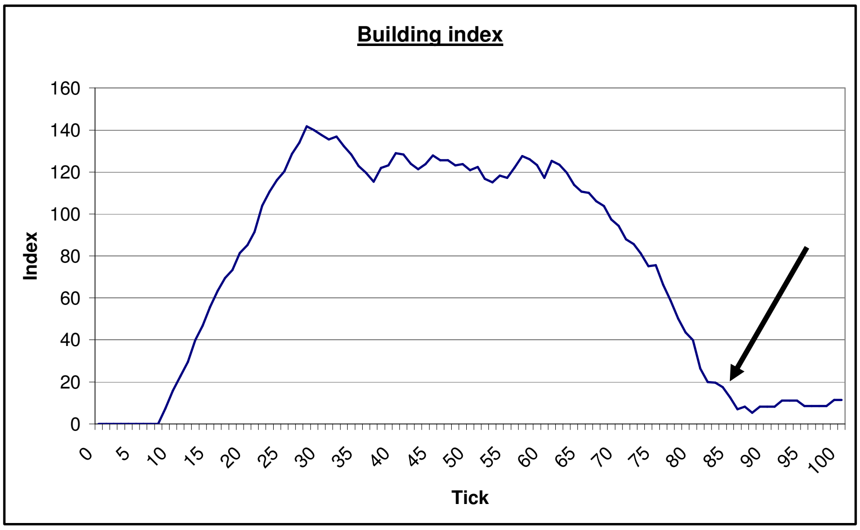
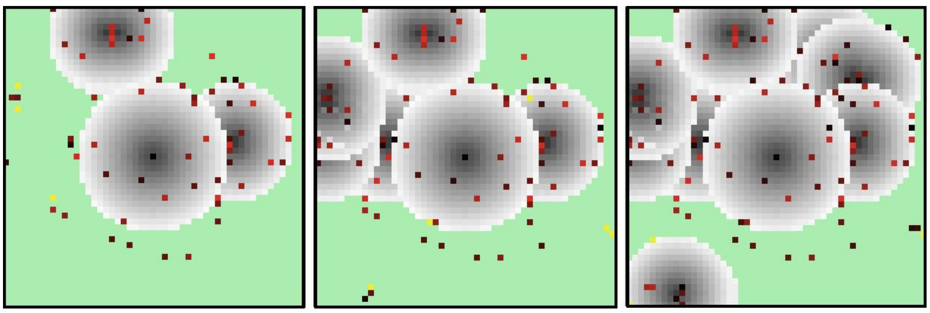


Figure 7: First stage of the building index in a polycentric city

Again, as low characteristic time available land is exhausted, developers with preference for immediate returns ("small") turn to alternative activities, but developers willing to speculate ("big" developers) can continue to purchase land in the periphery or can turn to buildings renewal through demolition and re-building. As time passes, the building index is prone to fall again below the threshold, leading to new rounds of intensive sub-centers development resulting from the same approval and characteristic time changes dynamics. Figure 8 illustrate several development runs, until there is no more available land for development. In particular, in the right side of the lower row there is a clear example of leap-frogging.



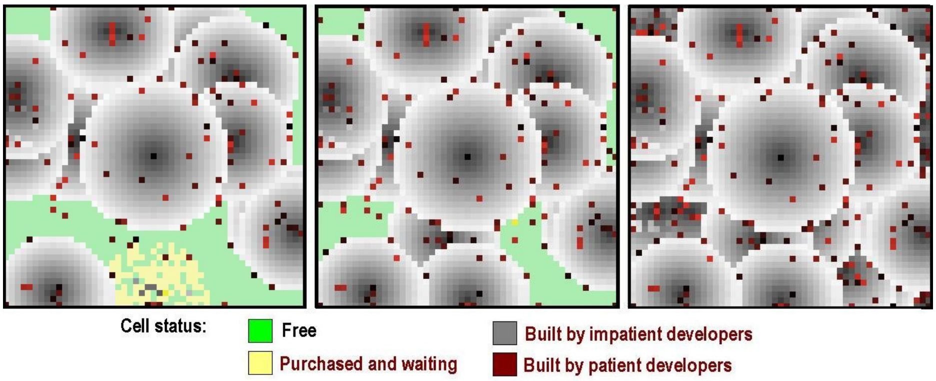


Figure 8: Polycentric city development

The building index monitored by the municipality reflects the city dynamic development process, as depicted in figure 9:

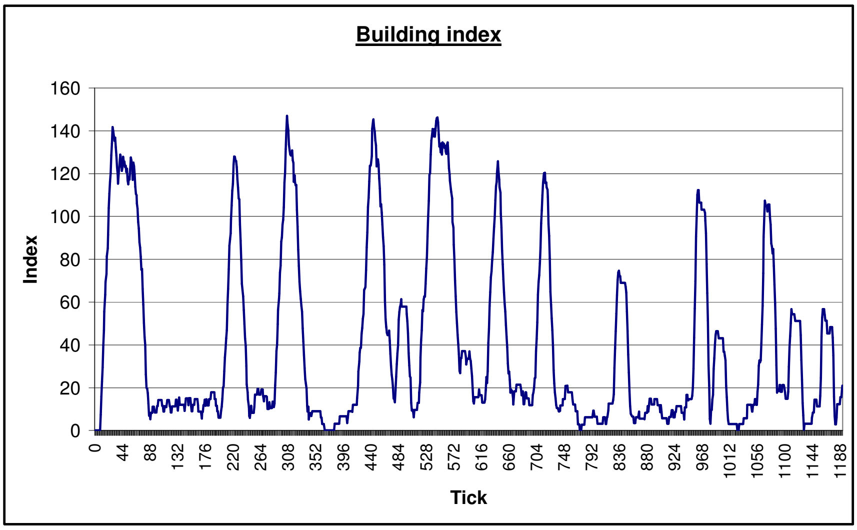


Figure 9: Polycentric city development reflected by the building index by time

The cumulative construction activity reflects the trends observed in the building index graph (Figure 10). It is characterized by short periods of steep slopes (the sub-centers construction bursts) followed by relatively long periods of minimal activity (when only "big" developers are active).

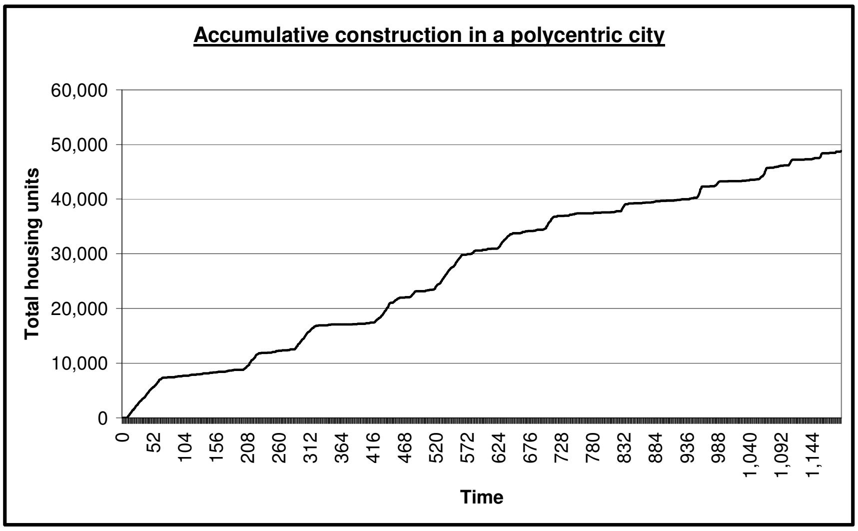


Figure 10: Construction activity in a city with heterogeneous developers

The polycentric structure of the city can be demonstrated using the height transects, which clearly reveal some of the sub-centers created around the CBD:

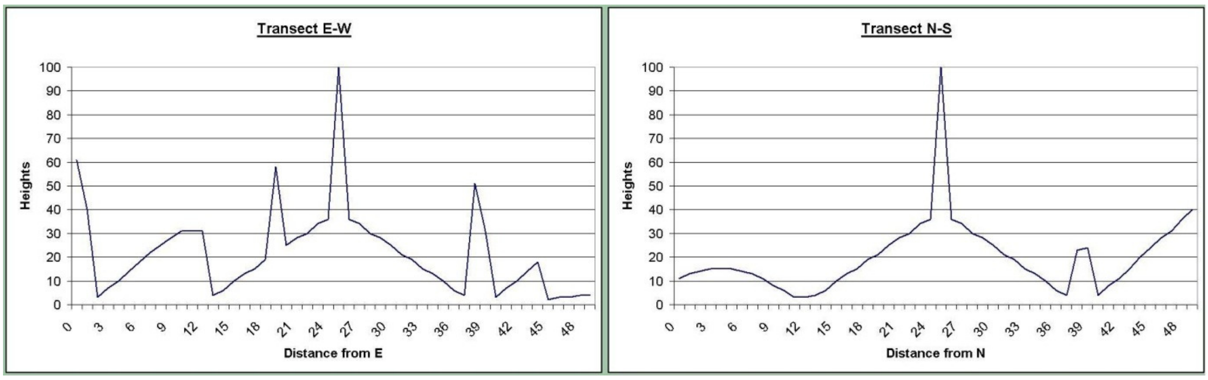


Figure 11: Height transects of a polycentric city

An additional description of the polycentric city structure is from above, isolating buildings between certain ranges of heights. In the following figure, selected height ranges are marked by levels of gray Low rise buildings (less than 10 stories) shows clear concentric patterns around their respective sub-center (brighter gray pixels), and so medium rise buildings (between 11 and 30 stories, in gray pixels) but high-rise buildings (more than 31 stories) are located in the middle of their respective sub-center but also scattered without an easily recognizable pattern (black pixels). The reason is that low rise buildings were built by "small" developers attracted to a site because of the relatively low characteristic time, and therefore their height reflects the characteristic time function behavior. In contrast, "big" developers are much less influenced by time constrictions and therefore they construction patterns are much more random.

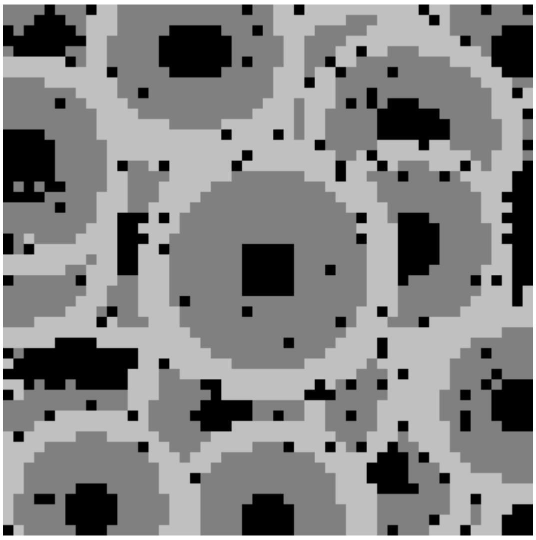


Figure 12: Heights from above. Bright gray pixels represent low buildings (less than 10 stories), gray pixels medium buildings (11-30) and black pixels high rise buildings (more than 31 floors)

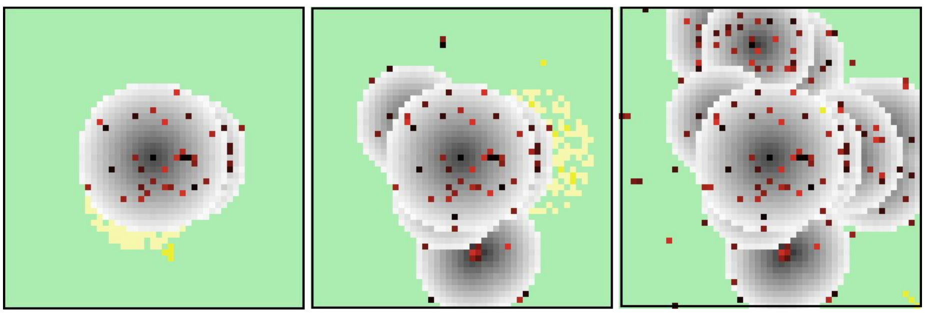
<u>Third scenario: Heterogeneous developers (10 "small" vs. 2 "big")</u>

In this scenario a heterogeneous group of developers is allowed, but the proportions between the developer's types' changes: Two "big" developers are participating with 10 "small" ones. The same dynamics described in the previous one are expected, but the development rhythm is different. The following table defines the key parameters of this scenario:

Parameter	Value
Number of "small" developers	10
Number of "big" developers	2
Radius of the area allowed for new urbanization	10 pixels

Table 4: Third scenario key parameters

The following figures describe the city spatial development process. Similar patterns than those described in the previous scenario are shown, but at a faster rate:



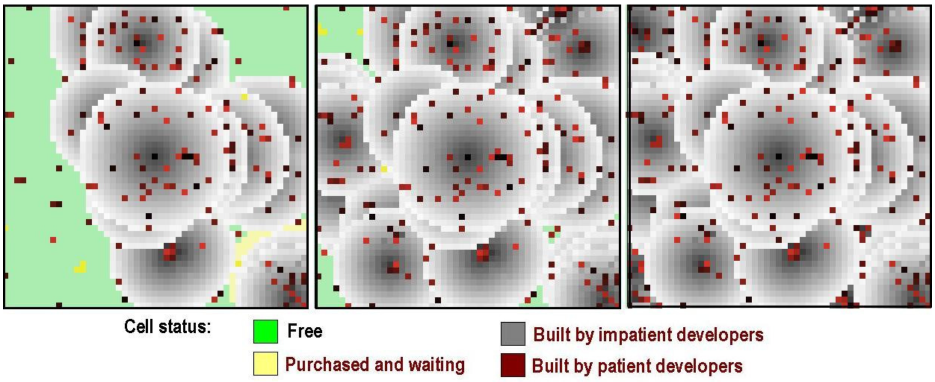


Figure 13: Polycentric city development (10 "small" vs. 2 "big" developers)

The significant change in the intensity and the velocity of city development can be fully appreciated in the following picture, which compares the building activity of this scenario with that of the previous one. The city is fully developed faster if two "big" developers are active, and the number of built houses is much higher. This result is the outcome of the higher pressure exerted on the planning authorities by a population of "big" developers which is twice bigger than in the previous scenario (which leads to quick development areas release) combined with the higher buildings erected by them.

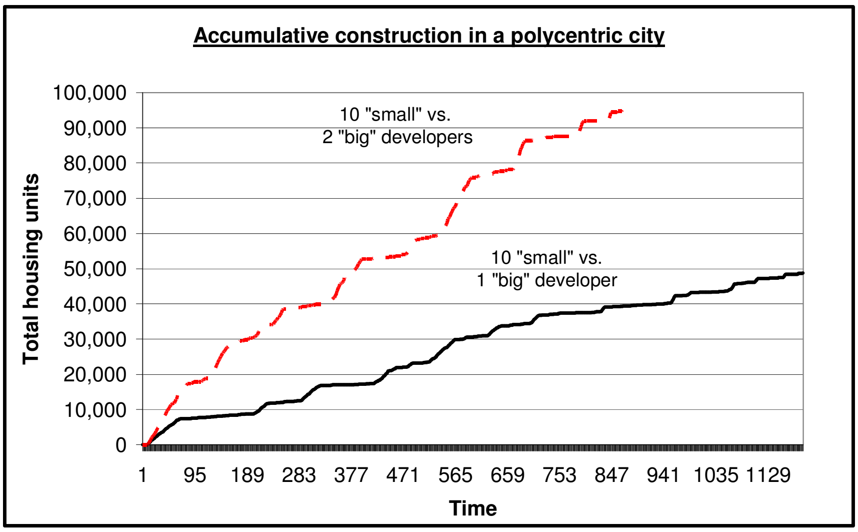


Figure 14: Construction activity in a city with heterogeneous developers and different proportions between types

<u>Fourth scenario: Heterogeneous developers with smaller development allowed area</u>

As was explained in the previous two scenarios, the relative proportion of "big" and "small" developers has a dramatic influence in the urban spatial development cadence.
However, the characteristics of the developer's active in a city are presumably an outcome of the city economic attractiveness, but less a result of planning authority's policies. Therefore, in

order to assess planning policies, it is interesting to test the model sensitivity to a parameter that is fully controlled by city planners and decision makers. This parameter is the area allowed for new urban development once the building index falls below its lower threshold. In all the previous scenarios it was assumed that this radius is defined as 10 pixels around a new high-rise buildings pole erected by "big" developers. In this scenario we assume a more restricted response by city planners, allowing new developments on a smaller area, with a radius of 5 pixels.
The following table defines the key parameters of this scenario:

Parameter	Value
Number of "small" developers	10
Number of "big" developers	1
Radius of the area allowed for new urbanization	5 pixels

Table 5: Fourth scenario key parameters

Obviously, since new development areas are smaller, the spatial development process is slower compared with the case of 10 pixels radius. The following graph shows the difference between both policy options:

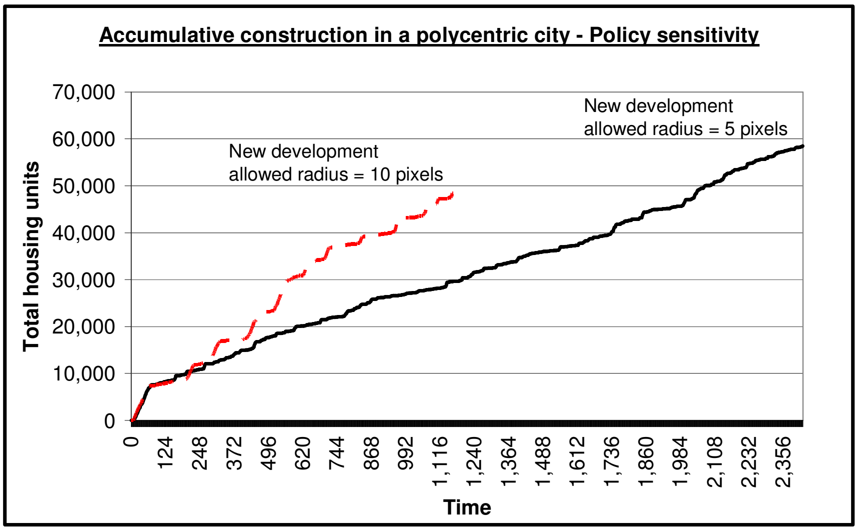


Figure 15: Construction activity in a city with heterogeneous developers and different development allowed areas

Another important difference between those two policy options is that the development intensity of the city is higher when the allowed area is smaller. Since developers' time impatience is fixed, smaller allowed areas imply that impatient developers will build higher buildings in order to maximize profits. Although "big" developer's behavior does not change under different city policies, changes in "small" developer's behavior are enough to provoke an overall more intense development. The next figures show the final city configuration and the heights distribution for the case of development radius of 5 pixels.

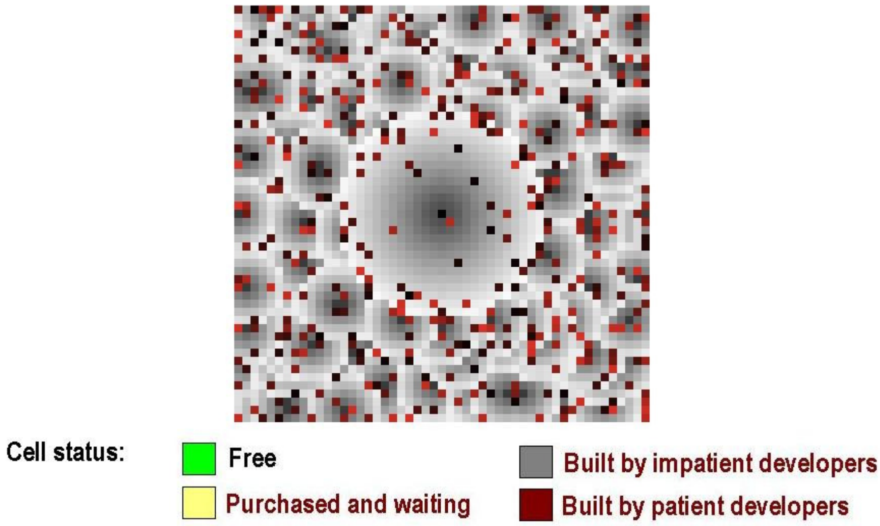


Figure 16: Final stage of a polycentric city development with development radius = 5

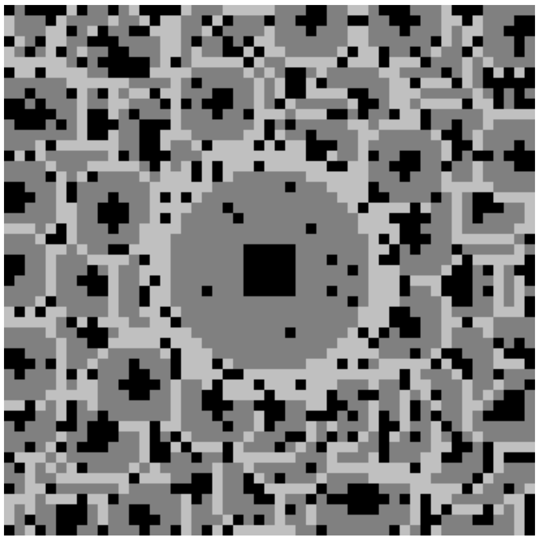


Figure 17: Heights from above in a city with development radius = 5. Bright gray pixels represent low buildings (less than 10 stories), gray pixels medium buildings (11-30) and black pixels high rise buildings (more than 31 floors)

Discussion

The basic, traditional urban economic models (Alonso 1964, Mills, 1967, Muth, 1969) are powerful tools able to explain the main forces behind cities' development. However, their spatial outcome assumes the form of a well organized mono-centric city, a pattern which is hardly verified in any modern city (Irwin & Bockstael 1998, Wha et al 2011, Serra & Pinho 2011). Several efforts were invested enriching the basic model in order to explain sprawl and scattered development, for example assuming landowners inter-temporal planning (Mills

1981), perfect foresight of land rent value (Wheaton 1982, Fujita 1982) or dynamic residential processes (Turnbull 1988). In most of those models, municipalities' regulation roles and planning policies are neglected, or at least assumed to have little influence. We claim that the combination between urban planning policies and developer's behavior can explain much of the city spatial development patterns. In previous papers the influence of the characteristic time imposed by planning authorities on leapfrogging dynamics in linear spaces was analyzed in a single city model (Czamanski & Roth 2011) and assuming two interacting municipalities (Czamanski & Broitman 2011). In this paper our objective is to explore the assumption that different types of developers exists ("big" and "small", characterized by scale of operations, availability of own-capital and time preferences) which are differentially affected by city planning policies expressed as spatial characteristic time settings, and some of them are able, in turn, to influence on those policies.

There is growing evidence that urban development can be considered a complex system (Wilson 2006) with self-organizing characteristics (Kumar et al 2007). Moreover, some scholars claim that cities and networks of cities may represent a case of self-organizing criticality (Batty & Xie 1999, Chen & Zhou 2008). The insights that our model can reveal exploring such issues are beyond the scope of the present paper, but they seem promising and therefore we suggest them as possible futures lines of research.

Conclusions

While traditional urban models cannot explain the formation of polycentric urban development patterns, here we explain it by analyzing the interaction between real estate developers' choices and municipal planning policies. While planning policies differ among countries, in many places zoning variances are possible. Our model indicates phase transitions in the urban spatial configuration as a result of the behavior of homogenous "small" developers or a mix of "small" and "big" developers. Sprawling suburbs, scattered land development and sub-centers emergence follows the complex dynamics created by "big" and "small" developers’ choices in time and space. These results shed light on possible outcomes of planning policies, in particular of restrictive development policies that at times become counter-productive. The resemblance between the spatial dynamics resulting from our model and Self Organizing Criticality models' outcomes suggests that further research on linkages between them is promising.

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4.4. Paper #4

Bursts and avalanches – the dynamics of polycentric urban evolution

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Abstract

Urban construction activities are subject to periods of fast expansion followed by periods of slow growth. Some of these expansions are limited is size, while other are huge. Therefore, it is not surprising that equilibrium oriented classical models of urban spatial structure are hard pressed to explain the formation of modern cities with polycentric structure and births of sub-centers in particular.

To understand the development of cities' spatial pattern we develop a model of urban spatial dynamics that is driven by real estate entrepreneurs of two types that differ in the degree of risk aversion. The developers act in light of city planning committee that formulates urban development policy. Its salient feature is the time lag between the moment of purchase of property rights by land developers until the realizations of revenues. We assume that this lag varies in space and can be reduced in case of high demand for dwellings.

With the model we demonstrate how the interaction between demand for dwellings, developers' choices and planning policies lead to the creation of new urban sub-centers. Model dynamics is characterized by long out of equilibrium periods followed by sudden bursts of construction activity that resembles self-organized criticality (SOC).

1. Introduction

At the backdrop of the spatial dynamics of cities there is an adverserial interaction of land developers and planning authorities. Urban planners seek to advance the public's interest by efforts to prevent sprawl and to ensure accessibility to open spaces. This they do by promoting dense settlements by restricting the locational and other decisions of developers. Among other things, planners determine the location and intensity of land-uses by specifying types of building that can be constructed within the municipal territory. In some places building activity is not allowed. At some locations restricted construction activity is permitted. The relaxation of building restrictions involves concentrated effort by developers and prolonged procedures. The result is the issuance of building permits and consequent varying number of building starts (EUROSTAT, 2010, US Census Bureau, http://www.census.gov/const/www/newresconstindex.html).

The adversity between planning authorities and developers is not uniform in space and time. In cities in which population growth is stagnat and during periods of macroeconomic downturns low demand leads to lethargic behavior of developers. Some developers utilize such periods to purchase land parcels for future development, including land that is not zoned for development. Periods of rapid population growth and economic expansions create high demand and consequent housing price bubbles (Glaeser et al, 2008), fervent search by developers for all available, developable land parcels and eventual construction booms. Thus for example, the immigration to urban centers in USA starting in the mid-1960s and vast immigration wave from the former Soviet Union to Israel in the early 1990's caused scrambling behavior by developers, housing price volatility (Benchetrit et al 2008), construction booms, urban economic restructuring and changes in settlements patterns (Waldinger, 1989; Spelman, 2009; Beltratti et al, 2010).

However, aggregate building starts data tell an incomplete story. Casual examination of figures 1 and 2 below suggests that the combined effects of macro-economic cycles and immigration flows tell a partial story only. Thus, although the effect of immigration from the former Soviet Union on Israeli cities and of the 2007 downturn in the USA is easily recognizable in the charts, there are clear local trends that do not seem to be related to these phenomena. It seems that there are local forces generating additional, more refined, cycles of fast growth followed by periods of slow growth. Furthermore, these building starts data say nothing about the spatial incidence of these trends. There is growing evidence that the speed of spatial expansions in some cities displays irregular patterns (Liu et al, 2011) and that the process occurs at very different rates in different zones of cities (Cao et al, 2011).

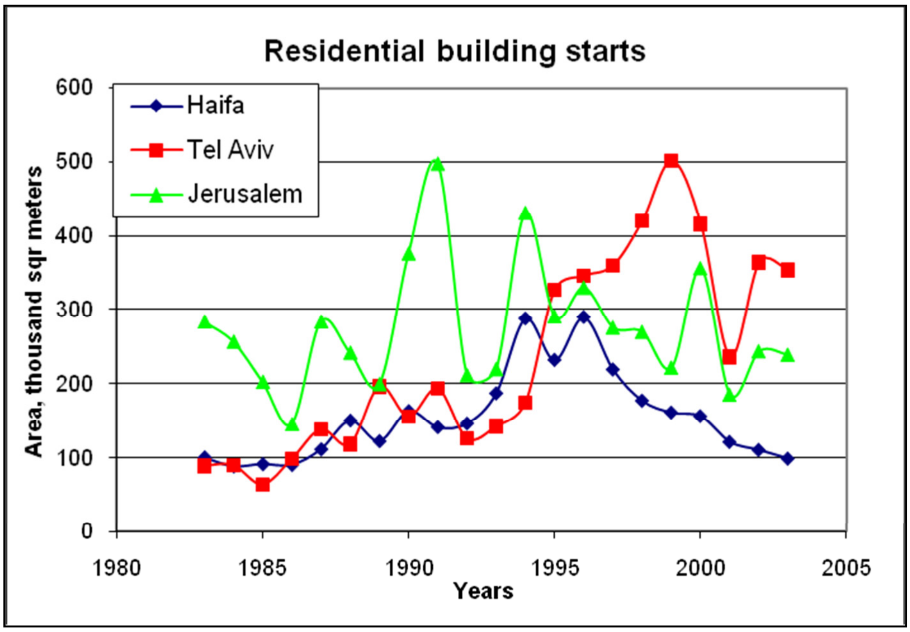
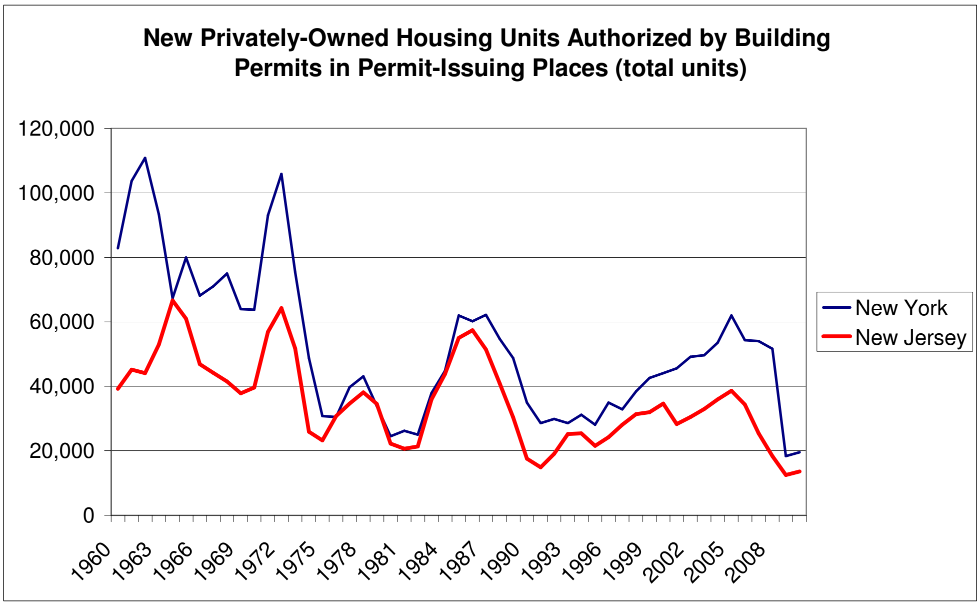


Figure 1: Building starts in major Israeli cities 1980 – 2005
[Source: Israel Central Bureau of Statistics]



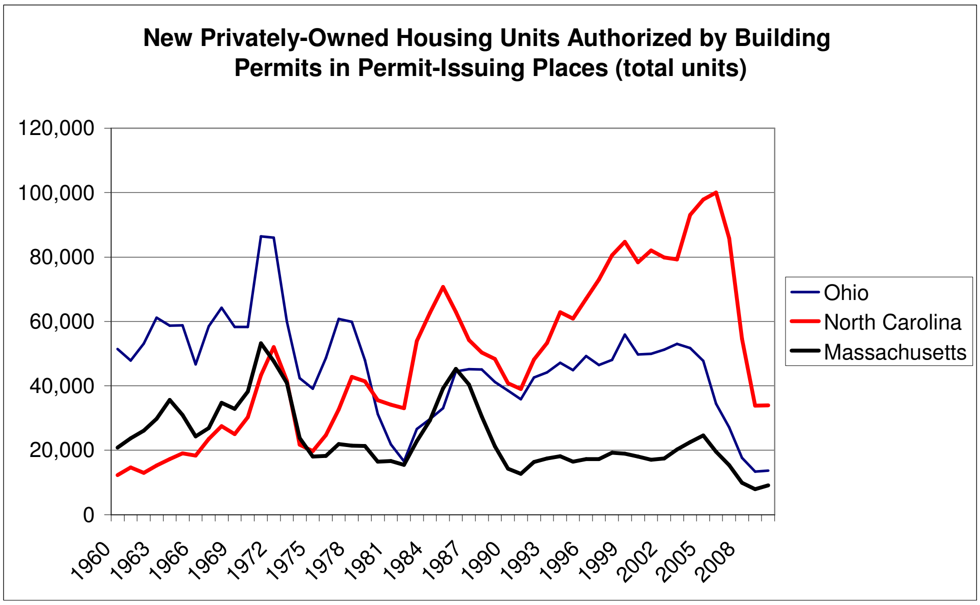


Figure 2: Building starts in selected USA states 1960-2010
[Source: http://www.census.gov/const/www/newresconstindex.html]

At least in part the fact that construction activities are subject to periods of fast expansions followed by periods of slow growth can be explained by variations in demand and willingness to pay that recurrently pushes the city as a whole away from an equilibrium state. Therefore, it is not surprising that equilibrium oriented classical models of urban spatial structure are hard pressed to explain the major emerging feature of the modern cities, namely the births of urban sub-centers and the resulting polycentric urban pattern. In fact, there is a paucity of models that are concerned with both the spatial and temporal evolution of modern, polycentric cities.

In this paper we suggest that beyond the familiar, global economic and demographic trends, urban spatial expansion dynamics are significantly influenced and fashioned by local forces. More specifically, we suggest that the interaction between municipal planning policies and profit-maximizing choices of investors in real estate projects in light of varying demand for dwellings in a city may explain much of the spatial-temporal evolution of polycentric cities.

In our analysis we are inspired by the possibility that the formation of urban spatial pattern is similar to the phenomenon of Self-Organized-Criticality (SOC). SOC was developed in order to describe the dynamics of non-equilibrium systems that respond to external perturbations with events of all sizes at no apparent characteristic scale. According to Per Bak "… systems evolve to the complex critical state without interference from any outside agent …Large catastrophic events occur as a consequence of the same dynamics that produces small ordinary everyday events" (Bak, 1996). The sand-pile metaphor is commonly used to illustrate conceptually SOC ideas (Bak, 1996; Christensen & Moloney, 2005). A wide range of SOC applications were developed in fields as diverse as physics (Christensen & Moloney, 2005, Dickman et al, 2000, Dhar, 2006; Bak et al, 1987, 1988; Bak, 1990, Carlson & Swindle, 1995), time series analysis

(Xianzhong & Sheng, 2010) and cellular automata models (Bak et al 1989, Alstrom & Leao, 1994; Sales, 1993).

Power law is a strong sign of SOC. For example, the sizes of the sand-pile avalanches follow this law (Bak, 1996). Some indications of SOC in the case of cities were obtained by means of the power law and of the fractal structure of the urban built pattern (Batty & Xie, 1999; Benguigui et al, 2000, Chen & Zhou, 2008). Our view of the relation between the SOC and urban dynamics is based on the Gabaix model of proportional growth of the cities (Gabaix, 1999, 2008 and Benguigui et al, 2007). The model assumes that, on average, the growth rate of cities is the same and that it varies randomly in time according to a normal distribution. Gabaix (1999) has shown that in such a system, in a long run, rank size distribution of cities follows the power law. We thus question whether there are internal regularities in developers' behavior that can cause the power-like distribution of the waves of urban growth.

The rest of the paper is comprised of three sections. In the next section we present an agent-based model that generates three dimensional, polycentric urban dynamics. In the following section we present the spatial and temporal evolution of cities generated by the model. In particular, we illustrate waves of spatial expansion that resemble bursts typical of the self-organized criticality. We conclude with discussion of our results.

2. Model concept

Our model describes the city growth as an outcome of the interactions between a planning board and land developers. The population of the city increases and urban planning board fashions land-use plans that defines where construction activities are allowed: Clear-cut administrative measures in the form of zoning restrictions define precisely the location and intensity of construction activities.

2.1. Characteristic Approval Time

Beyond direct statutory enforcement, there are more subtle ways in which city planners influence urban development. Since all construction projects must gain planning approval, the time and effort required of real-state entrepreneurs to achieve building permits at a certain location is a significant factor to be considered. Expected long waiting times, often due to the opposition of environmental lobbyists, may discourage potential entrepreneurs from initiating building projects. Construction permits within areas of municipalities that are zoned for buildings are expected to take shorter time to be issued than permits in other locations.

In general, we assume that in a mono-centric city, the time it takes to obtain a construction approval increases with the distance from the CBD. Furthermore, assuming that the environmental impact of physical structures is proportional to their height, we postulate that at a given location, the approval waiting time will be longer for higher buildings. We combine these assumptions assuming that *Characteristic Approval Time,* (CAT), the time elapsed from the purchase of property rights and until the realization of income from the constructed projects is monotonously increasing with the distance from the CBD and height of the project.

The planning policies implemented by planning boards change occasionally in response to changing conditions. In particular, we assume that as population grows and the city experiences excess demand for housing, the pressure by developers to approve construction, contrary to zoning regulations, can be approved. We introduced changes in planning policies as changes in the CAT.

2.2. Behavior of developers

We assume that there are two types of developers:
Small developers: These are small players that abide strictly by the planning regulations. They purchase land for almost immediate development within existing planning restrictions and not for future development after obtaining land-use variances. And, thus, they do not initiate changes in zoning regulations so as to realize a return on the land they already purchased. In the presence of "small developers" only with a preference for immediate returns combined with CAT that grows with distance from the CBD, one should expect the spatial structure of city to resemble an Alonso gradient.

Big developers: Some developers possess large time impatience. They purchase land for future development in the zones that do not allow building and at a low price. These are speculative purchases. The patient "big developers" will hold the speculatively purchased land until building will be possible after obtaining variance or until land-use plans are changed. In cases that many parcels of speculatively bought land are proximately located in space while the land in the core city is becoming scarce and demand for dwelling units is increasing, the planning authorities may change zoning rules and issue construction permits. After big developers start the construction, developers with a preference for immediate returns on investment will be able to move in and start building as well. As a result one can expect a new urban center to be created.

2.3. Planner's decision-making

The planner establishes zoning and Characteristic Approval Time (CAT) that grows with the distance from CBD. Beyond confounding development to the existing CBD, city planners have other objectives as well. The city's population is growing and over time, the authorities are required to keep housing supply growing as well. City planners monitor the number of households searching for dwellings within city boundaries and construction activity, expressed as number of built dwelling units. If population grows faster than dwelling supply, the excess demand the planner changes CAT or approves construction beyond the existing zones.

3. Model formalization

3.1. *Urban space:*

The city is developing on a square grid of cells, each of which represents a single parcel of land. Developers of all types engage in building activities only if there is excess of demand (i. e., there are currently households without dwelling). Initially, a single cell representing the CBD is located in the center of the grid and the cells within the distance R from the CBD center are available for development. We assume that characteristic approval time τ reflects the municipality counter-sprawl policy and τ increases with the distance from the CBD.

Developers' decision to purchase a land unit is based on two economic parameters: the customers' willingness to pay for a dwelling unit and price of the land parcel. Both decay with the distance from the CBD.

3.2. *Developers' decision-making:*

Formally, impatient developer seeks construction projects that can be implemented in a limited time T that is, the projects for which the characteristic approval time τ is T years or less, $\tau < T$. Since the characteristic time is a function of location and height, the impatient developer seeks parcels for which:

$$\tau(x,h) = \tau_L(x) + \tau_H(h) < T$$

where x represents the distance from the CBD and h is building height.

Although $\tau_L(x)$ is defined by the city planners, $\tau_H(h)$ is an endogenous variable representing decisions of developers and developer can, thus, adjust the height of the building in order to satisfy the T-constraint.

The impatient developer's decision algorithm is thus the following:

4- Choose at random, an available site where $\tau_L(x) < T$

5- Only if a site where $\tau_L(x) < T$ is available, calculate the minimal height $h_{\min}$ required in order to make profit based on the willingness to pay and the land cost. The willingness to pay is defined as $\max_{y \neq x}\left(h_y / d_{xy}^V\right)$ where y symbolizes all cells excepting x itself , h_y is the building height at y, d_{xy} is the distance between parcels x and y, and V is the attraction exponent. In a similar manner, the land cost is calculated as $\max_{y \neq x}\left(h_y / d_{xy}^W\right)$. The exponents used are $V = 0.5$ for WTP and $W = 1$ for the land price.
6- The maximal height of a building that an impatient developer will construct must allow him to wait no more than T time. Solving the equation $\tau(x,h) = \tau_L(x) + \tau_H(h) = T$ for h defines the allowed height. If $h \geq h_{\min}$ the impatient developer purchases the land, waits time T and builds a building of a height h. The construction itself is assumed to be instantaneous.
7- In all other cases (parcels with $\tau_L(x) < T$ or $h < h_{\min}$), the impatient developer will stay inactive until the next time unit.

The impatient developer's strategy is thus risk-free. They are assured that any project will be approved and finalized in less than T years.

The patient developer has two choices. As long as low characteristic time parcels are available in the urban core he behaves like the impatient developer. He differs from the impatient developer in one respect – the choices of building heights are random (not limited by time constraints). In this case the algorithm is the same for both types of developers. In the case that parcels inside the city are not available anymore to the patient developer speculates and buys land for future construction and future returns in the urban periphery. This case represents speculation because it is against the declared city policy. In order to obtain construction approval, the developer gambles for a future change in the municipality’s policy. The patient developer also aims at profitability but accepts time related risks:

1- If a site where $\tau < T$ is not available, search for an area outside the urban core. Such sites can be purchased at a very low price, representing agricultural use. They need to be sufficiently close to developed areas so that demand for urban land uses exist and willingness-to-pay is positive.
2- Calculate attractiveness of every available parcel outside the urban core. The attractiveness is defined by two conditions: Profitability (according to the same WTP and land cost calculations explained above) and the vicinity of at least one parcel already purchased by other patient developer. For a given level of profitability, the parcel with the higher number of neighboring purchased parcels is more attractive.

3- Purchase a parcel x with a probability that is proportional to its attractiveness and wait an undetermined time for building permit. If the construction permit is allowed, develop a project of height $h > h_{\min}$.

Patient developers' speculative behavior grows in volume when sites in the periphery receive building approvals. They are attracted by the peripheral sites since they have justified expectations to receive approvals in that zone, and, indeed, if the dwelling demand is high enough they will be able to develop closer sites. However, financial capabilities of the patient developer are limited. There is an upper bound on the quantity of sites that can be held in a waiting status. In our model we set this limit as four undeveloped parcels for each patient developer.

Clearly, the patient developer takes a different approach from the impatient one. In early stages of city development, when the city's core (i.e. sites where $\tau < T$) is still not fully developed, she will choose sites in it, but since she is not constrained by time, the projects will be considerably more intensive (i.e. high-rise buildings) than those of the impatient developers.

3.3. *Planner's decision-making:*

To decide on zoning or CAT, the model planner estimates urbanization pressure *U(x)* and compares it to the threshold value U_{Th}.The threshold represents the number of high rise buildings that can accommodate population that represents a certain percentage of the city size. If population growths at a rate of r percent, then the threshold for the initial center is $r \cdot \tau$

The urbanization pressure U(x) is calculated as

$$U(x) = \alpha \cdot ED + \beta \cdot P(x)$$

The excess demand for housing ED represents pressure exerted by a growing share of the city's population that is unable to find adequate housing and is expressed by the number of housing units calculated as number of buildings. The development pressure at a certain location $P(x)$ is a function of the number of sites purchased by patient developers beyond the planned urban area. We assume that sites close to concentrations of buildings will have a greater chance to be developed than sites located far away. Also, the higher are the building around the purchased site x, the higher is $P(x)$. The value of $P(x)$ is calculated for every undeveloped parcel x in the city as a weighted average of all neighboring building heights divided by their distance:

$$P(x) = \sum_{i \in N} h_i / d_{ix}$$

Where N is the set of cells at a distance of 6 units, h_i is their height and d_{ix} their distance from x.

α and β are parameters that are intuitively appealing. α is interpreted as a measure of the sensitivity of the planners to the pressure exerted by the growing population and β as sensitivity of the city planner to big developers' pressure. In our model we perform sensitivity analyses on both α and β

The planner thus acts according to the following algorithm concerning parcels at the city's fringe:

1- If $ED \leq 0$ (the dwelling supply meets or exceeds the existing demand), the planner issues approvals when the waiting time expires only in parcels where $\tau < T$
2- If $0 < ED$ but $\alpha \cdot ED + \beta \cdot P(x) < U_{Th}$ for each x, the planner issues approvals after waiting time expiration everywhere. That includes parcels where $\tau < T$ (urban areas) and parcels purchased by "big" developers.
3- If $U_{Th} < \alpha \cdot ED + \beta \cdot P(x)$, search for the parcel x that holds the highest potential, change zoning there and define characteristic approval time around it irrespective of whether a building exists in its vicinity. At this point the planner establishes a new zoning regulation. The new approved for development zone is circular, its area is proportional to $\alpha \cdot ED + \beta \cdot P(x)$, the characteristic time is lowest in the parcel x and T in the circle perimeter.
4- Once construction by big developer starts, characteristic time is reduced and developers with preference for immediate returns will return to build, creating a new Alonso-type sub-center.

Model results

In this section, we present results of model simulations and highlight particular features by isolating and exaggerating them. Among other things we investigated exponential growth of population as a rate within the interval of 0.01 – 0.02 per iteration. Another parameter that was investigated is the radius of the area around new urbanization seeds where the construction approval is obtained. In what follows we assume that there are many impatient developers with a preference for short-term return on investment and few patient developers who are ready to wait longer periods of time.

The city comprised of impatient developers is the simplest case. Under various sets of the relevant parameters the simulations always result in emergence of a mono-centric city with declining building heights as distance from the CBD increases. The model reaches quickly a stable equilibrium. The city structure is stable and there are no endogenous forces capable of pushing it away in any direction. The planner has no means to accommodate additional population that just increases.

The situation changes once a single patient developer is allowed to play. At the initial stage a mono-centric Alonso-type city is developed around the initial central cell, mostly by the impatient developers. The big developer participates in this process, but in parallel purchases land parcels beyond the zone permitted for construction (a maximal number of four undeveloped parcels at a given time). According to their behavior rules, the probability that the "big" developer will purchase next site close to the previous purchased sites grows with the increase of the number of the purchased sites around, and, thus, the purchases of the big developer are concentrated more than it could be for the purely random purchasing process.

When the existing city area is exhausted the planner is faced with a growing dwelling demand on the one hand and increasing pressure of the big developer for construction approvals on the other. The values of U(x) thus grows for every parcel x and, eventually, exceeds at some location the threshold U_{Th}. The planner issues construction permission at this x, which is usually one of the largest clusters of sites purchased by the big developers. The model is thus periodically driven out of equilibrium - periods of graduate development are interrupted by the bursts of activity of several sizes that occur at unexpected times. These large scale events result in emergence of the new urban sub-centers.

The model dynamics thus resembles the sand-pile SOC metaphor, at least in the sense defined in Frigg (2003). Purchased units are grains of sand and the city is a sand-pile. The patient developers' choices act as the sand grains falling according to self-attracting purchase process. Planner's permission in respect to the growing demand and developers' pressure releases an avalanche.

Let us characterize model dynamics by the number of dwelling units constructed at each time step. Figure 4 present this dynamics in the case of 10 "impatient" and a single "patient" developer for the case of $\alpha = 1/200$ and $\beta = 3/4$. The model dynamics is characterized by periodic raise of demand for housing ED (Figure 5), accumulation of sites purchased by big developer beyond the city boundaries (Figure 6) and urbanization pressure U. Eventually, the urbanization pressure reaches the threshold and the planner approves construction beyond the existing zoning. The approval results in a construction burst that gives rise to a new sub-center (Figure 7, 8).

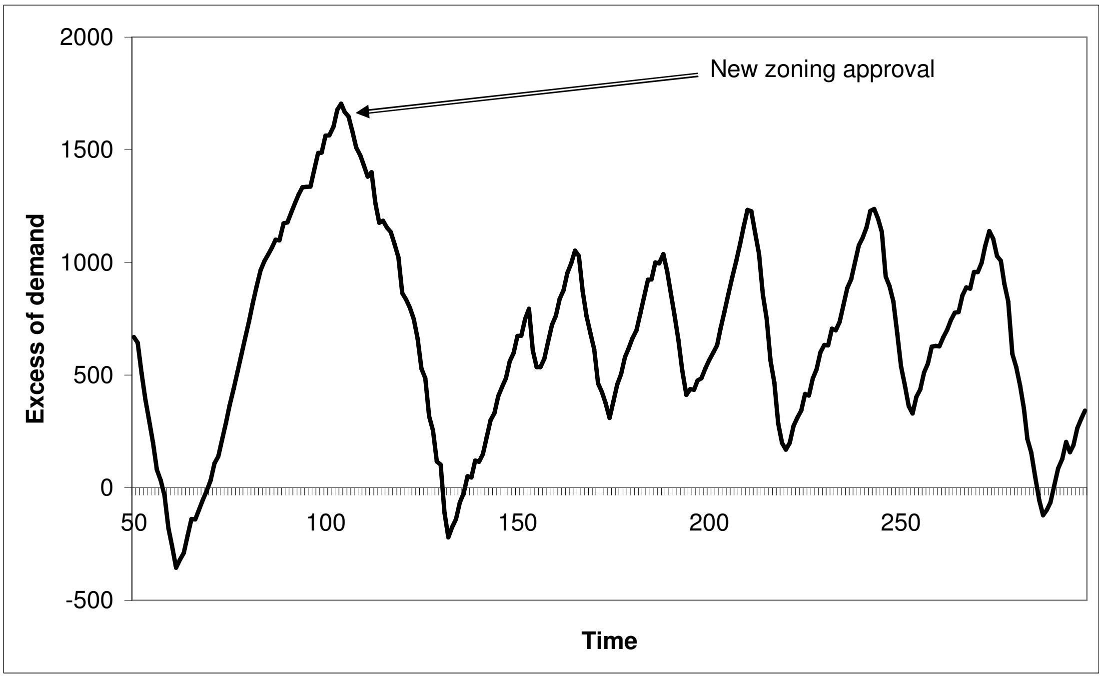


Figure 5: Excess of demand over time

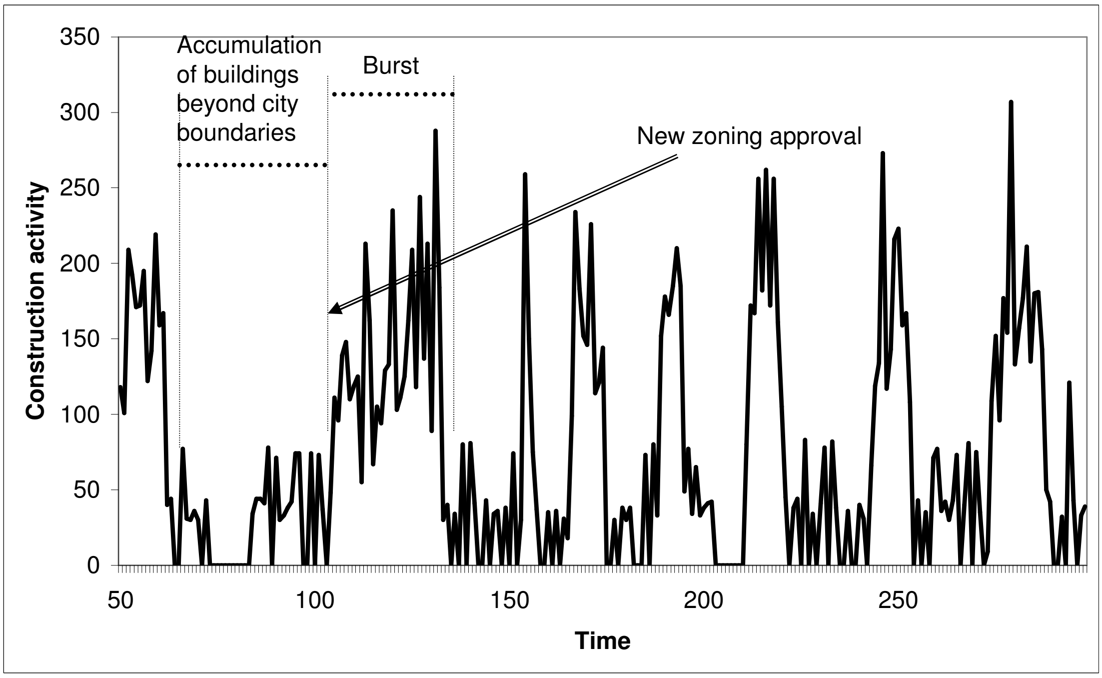


Figure 6: Construction activity as a function of time

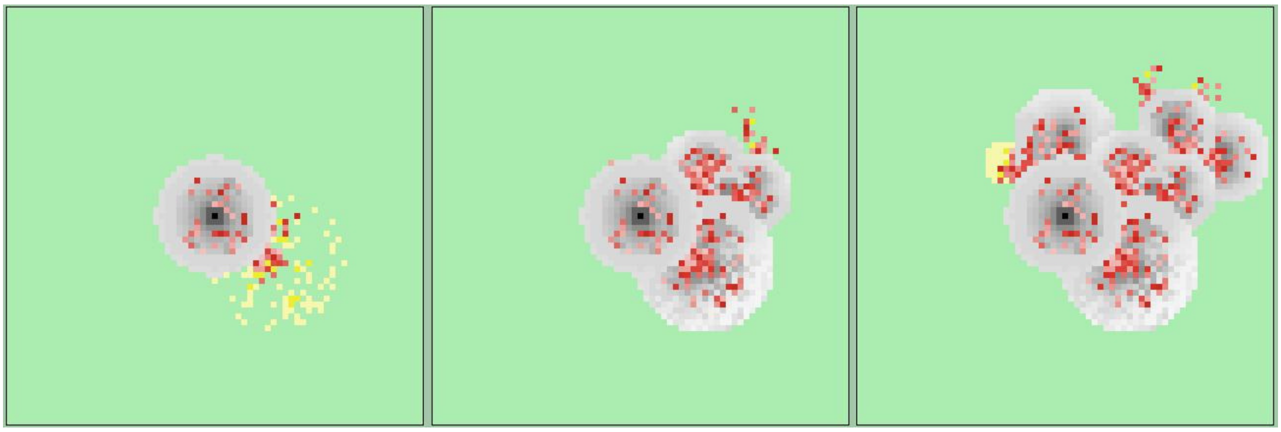


Figure 7: The formation of polycentric urban structure in a model with a 10 impatient and 1 patient developers in a 70 x 70 grid. From left to right, at time 100, 200 and 300

It is noteworthy that the size of the bursts and time intervals between them vary. Some bursts and intervals are relatively large and others are rather small.

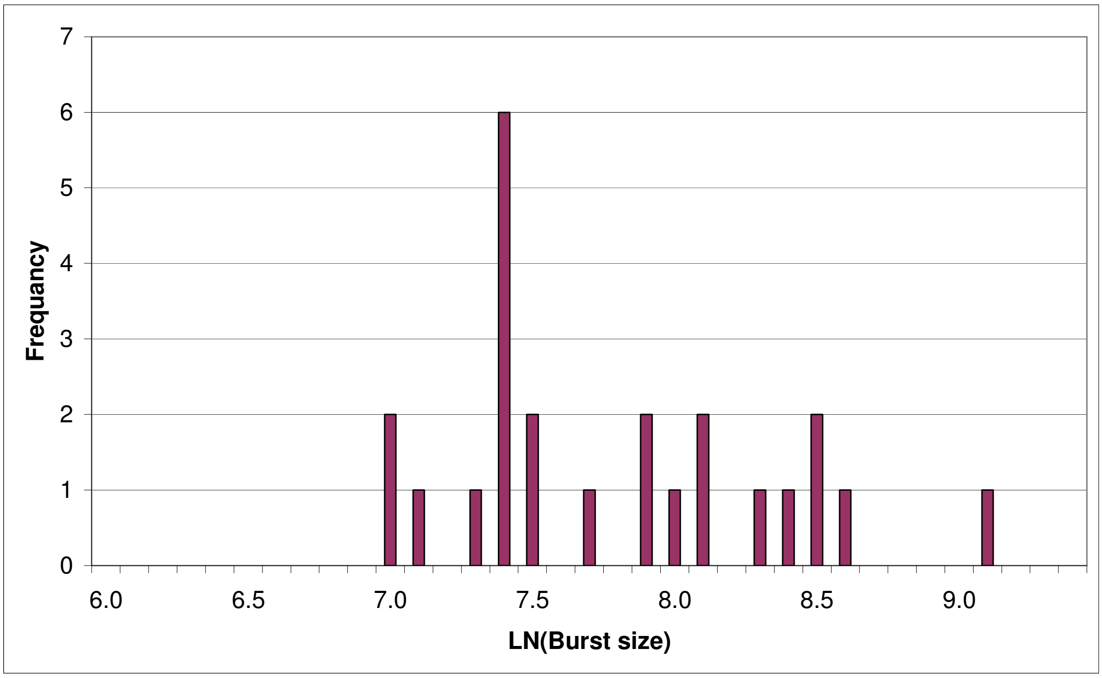


Figure 8: Frequency distribution of bursts

The polycentric structure described above is associated with an unbalanced number of patient and impatient developers (many more impatient developers than patient ones). It is noteworthy that as the share of patient developers increases, the resulting urban pattern is quite different.

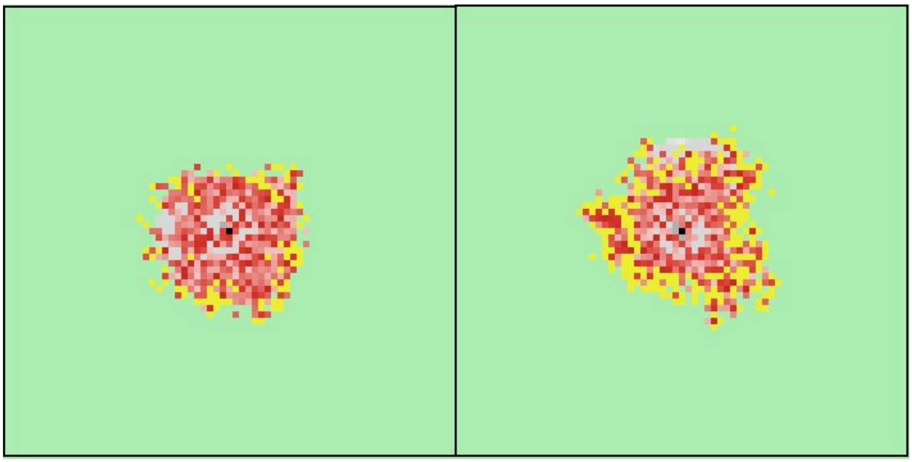


Figure 9: City Spatial structure with a large majority of patient developers

The left side of figure 9 depicts the city structure when 10 impatient and 20 patient developers are present, at time 300. The right side is the resultant structure when 50 patient developers are active with an equal number of impatient developers.

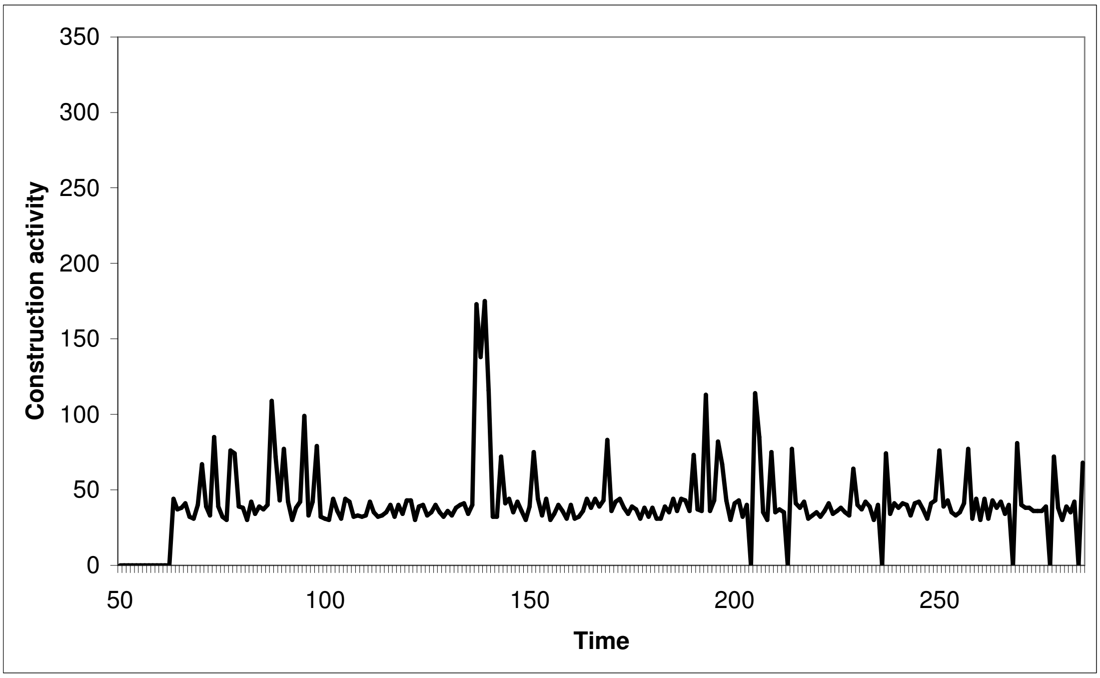


Figure 10: Construction activity when 20 patient and 10 impatient developers are present

The above illustrations are suggestive. They indicate that polycentric city is a continuous evolving structure between two extremes. An ordered world of impatient developers leads to the classical Alonso type city. A completely unordered, or entropic city, is the result of building activity of patient developers only. The polycentric structure that is so familiar to us is the result of a particular mix of the two types of developers. Their numbers suggest that only some pressure exerted by excess demand for housing and by developers seeking economic rents on agricultural lands results in construction activity and the formation of new sub-centers.

Finally, figure 11 presents the rank-size distribution of big bursts in the case of 10 impatient developers and 1 patient one. This distribution follows power law and can thus serve as an evidence of the SOC. While the fit is not perfect it is certainly suggestive. These results suggest that SOC is a valid framework for the analysis of our urban model.

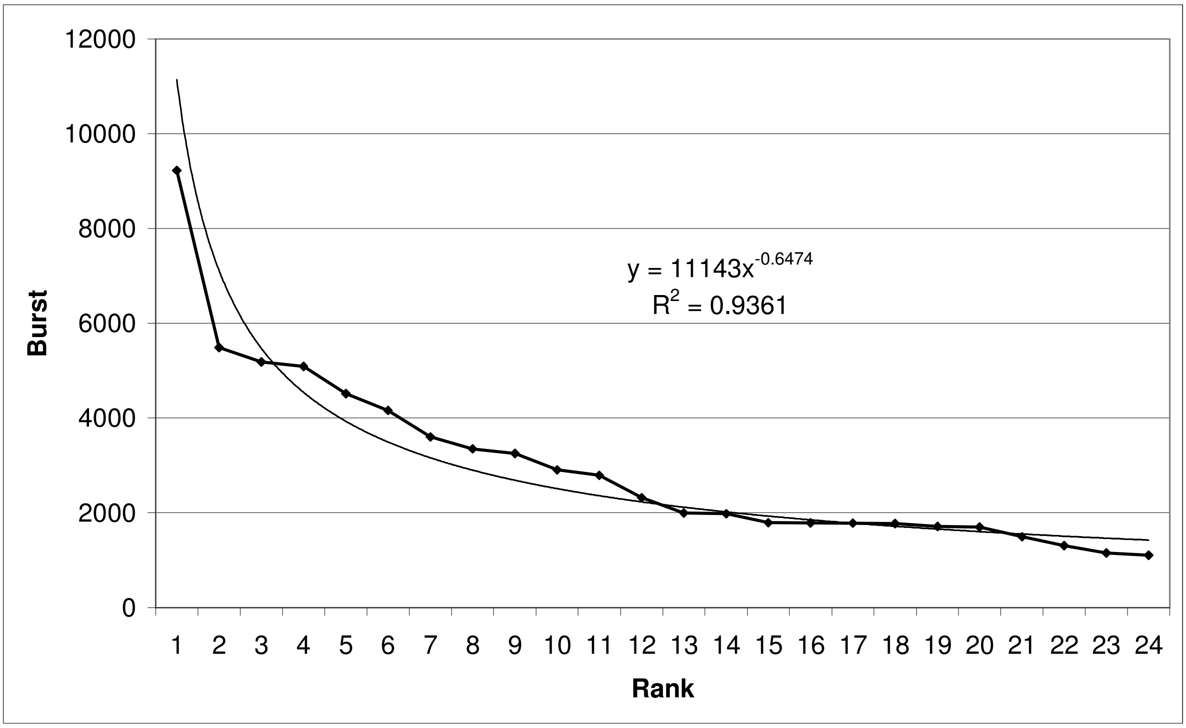


Figure 11: power law fit of urban bursts

The lack of a perfect fit is not surprising. It is well recognized that power law fit "may be only approximate in practice, and may hold only over a bounded range" (Gabaix, 2008). It has become accepted to remove the very many small centers to improve the fit.

Discussion

The study of the model suggests that the adversarial interactions between planning authorities and developers lead to the discontinuous in space and time release of lands for development and, thus, leads to the creation of polycentric urban structure.

The rules that govern the planner's behavior lead to the emergence of small clusters of buildings of various heights in peripheral sites. When such clusters become concentrated enough, city planners realize that the slow high-rise building permissions dripping created the seed of a new urban sub-center, and that the specific peripheral zone will become urbanized. The municipality then relaxes the characteristic time constraints in that zone, setting it lowest in the new cluster, and gradually increasing it outwards. A large set of new locations where $\tau < T$ is created, and therefore new opportunities both for patient and impatient developers arise. Both devote themselves to the new sub-center development, giving rise to a construction boost which pushes the excess of demand far below the threshold. The increased activity continues until the new sub-center is fully developed, followed by a new stagnation period, when the whole process is expected to happen again.

The burst phenomenon is due to the fact that planning authorities are bounded by land-use zoning and otherwise resist granting building permits for massive developments e.g, at the city's edge. Population growth and consequent excess demand for housing that does not receive response within the city's boundary creates pressure for granting of building permits beyond the planned zones and leads to the establishment of new centers of urban development. Once the building process starts, the initial big developer is joined by others, including small developers, and a significant sized burst occurs.

The timing of the peaks and troughs in construction activities depend on the relative number of the two types of developers. The land purchases by the big developers and population growth are similar to accumulation of energy in physical systems. Planning authorities, in response to market pressures, release this energy. Just as in the sand-pile, the energy of population is accumulated continuously, but can be "spent" in two ways: (1) as a result of construction by impatient developers that follows standard long-term zoning and CAT; (2) purchase and construction activity initiated by the patient developers and followed by the impatient developers. The first process resolves the routine problem of dwelling demand and is hardly perceptible to the system observer. The urban changes of a second type look like bursts and lead to qualitative changes in the urban pattern. Changes in the behavior of planning authorities in response to accumulated urbanization pressure leads to qualitative changes in the spatial structure of cities. Thus, it is the behavior of planning authorities that plays a key role in the formation of polycentric urban structures.

The periodic formation of new urban centers is influenced by the sensitivity of planning authorities to growing excess demand for housing (alpha in the model), and the pressure that developers have to impose on the municipality (beta in the model). The lower are the alpha and beta the stronger is the resistance of the planner to demand and to developers' pressure and, consequently, the longer the time until the new seed of urban activity will emerge. The demand will be transferred to other cities and the investment of the big developers nearby will not be returned.

There is a need for empirical analysis of the behavior of planning authorities and developers in order to reveal the nature of these parameters. In particular, there is a need to examine whether alpha and beta are constant or the pressure of demand and developers cause their growth and thus, the emergence of new urban centers becomes inevitable.

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5. Discussion

5.1. Answers to research questions

The overall objective of this research is to expand the current knowledge about the spatial and temporal dynamics of urban development, in particular, the creation of urban sub-centers. The goal is to offer new and alternate explanations to ubiquitous urban phenomena as sprawl creation, scattered urban development patterns and subordinate central business districts emergence, analyzing their dynamic behavior in time and space.

By means of the set of models developed during this research, the present thesis proposes a comprehensive response to the following research questions:

What are the factors that determine and drive the rise of new subordinate urban centers?

The shared feature of all the models developed is the existence of a spatial variation in characteristic time over the urban area. This characteristic time function reflects city planner's preferences and perceptions about the optimal size and shape of the city. From the point of view of profit-maximizing real estate developers, the characteristic time is a constraint which impacts on their objective profit function. The adversarial interaction between these two factors stands at the background of each one of the models.

In the case of two similar cities in a linear space, planning policies are expressed by the characteristic time imposed by each one of the municipalities. These provoke an immediate influence on the land developer's location choice. Whether if the neighbor cities implements myopic policies or engage in competence with each other, and regardless their planning objectives, spatial variations of the characteristic time creates plenty of opportunities for a profit-seeker developer. One of the reasons for this result is the existence of an administrative border and the ability of each city to define development rules only on their side. As a result, a new urbanization which can underpin a sub-center emergence is created.

When considering the case of two qualitatively different cities in a linear space, a new factor arises. On the top of the previously described considerations there is an additional factor which is not under the control of any of the actors: The willingness to pay in a specific location, which is derived from the attraction forces emanating from both cities. Although the WTP function is given in any single place, it affects greatly the developer's profits. Indirectly, the WTP variation influence on the required municipalities' policies, assuming that they are willing to compete attracting developers to their territory. Once again, the creation of a new sub-center is the result of the interaction between land developers and city planner's.

This adversarial interaction is made explicit in the agent-base model. Municipality officers are able to define the characteristic time in each location, and modify it dynamically as the conditions change. Patient and impatient developers make decisions according to the relative profitability of available sites, and the constraints defined by the characteristic time. All this parameters evolve over time as parcels are being occupied and developed, and as the urban structure develops. In this case the sub-center emergence takes the form of construction bursts, in which all developer's types are engaged.

The results are consistent regardless the type of model used. The interaction between planning restrictions and profit-seekers developers give rise to new urban sub-centers.

Which models are able to simulate urban sub-centers emergence?

To a certain extent, as papers 1 and 2 demonstrate, it is possible to simulate the principles behind complex urban dynamics using simple comparative static's tools. However, this is true only if the goal is to illustrate what is the first step of a dynamic process, using homogeneous agent's representation. These tools are not well fitted for studying dynamic processes or implementing heterogeneous agents. Since these were the goals of the later research stages, the agent-based approach was implemented. The flexibility embedded in this type of tools and the ability to define relatively simple micro-motives to heterogeneous agents proved very fruitful for the research proposes. The macro-outcome, in this case the dynamic and asynchronous sub-center emergence, was observed and measured regardless the simple model settings. As a conclusion, simple tools as comparative static's are enough to illustrate general principles, but if a dynamic and heterogeneous framework is needed, agent-base models were proven to be a powerful simulation platform.

What are the spatial-temporal dynamics of the emergence of sub-centers at the urban scale?

As stated previously, the spatial-temporal dynamics of the sub-centers emergence can be simulated using agent-based models as those developed in the framework of this research. Once the central part of the city is fully developed, impatient developers run out of construction business due to the lack of opportunities. Patient developers are constrained to small clusters of buildings in peripheral sites, because of the rules which govern the planner’s behavior. In the meantime, there is a growing unsatisfied demand for dwelling. When such clusters become concentrated enough, city planners realize that these peripheral clusters created the seed of a new urban sub-center. Therefore the municipality chooses the most influential cluster, relaxes the characteristic time constraints in that zone, setting it lowest in the new cluster, and gradually increasing it outwards. A large set of new available locations is created, and new opportunities both for patient and impatient developers arise. Both devote themselves to the new sub-center development, giving rise to a construction boost which alleviates the excess of demand for dwelling. The increased activity continues until the new sub-center is fully developed, followed by a new stagnation period, when the whole process is expected to happen again.

The first sub-center emergence occurs only after no available development land is left in the central city. Therefore, the first stagnation-burst cycle timing depends on the city planner's perception of the efficient and desirable urban physical area. If the city structure is perceived as a restricted urban area immediately surrounded by an agricultural or open-space hinterland, the subsequent urban development policy will be defined by high characteristic times around the original CBD. In the first city development stages, both patient and impatient developers will search for free parcels within a restricted area, since beyond a short distance from the CBD the characteristic time will be above their willingness to wait threshold. If, otherwise, the city is perceived as a larger urban core with a remote and well differentiated hinterland, the characteristic time function defined by city's authorities should be much more relaxed, allowing a wider range of development possibilities.

The subsequent timing of the peaks and troughs in construction activities depend on the relative number of the two types of developers and by the sensitivity of planning authorities to growing excess demand for housing and the pressure that developers have to impose on the municipality. The stronger is the resistance of the planner to demand and to developers' pressure, the longer the time until the new seed of urban activity will emerge.

Can urban sub-centers emergence be explained in a credible and reliable manner using urban economics and agent-based models?

Urban development process includes several stages, as searching for a suitable land parcel, purchasing development rights on it, obtaining appropriate zoning for the project, constructing it and finally, selling the real estate product. Characteristic time was defined as the period between the purchasing of land rights by developers until the realization of income from it. Among practitioners of land development it is well-known that the characteristic time, as defined here, is a critical variable in their decision-making process. This is particularly true when several planning boards exist. In this case the characteristic time includes formal plan deposition and the time until the plan is approved or rejected in each board. Therefore, the fundamental concept of "characteristic time" is well anchored in the land development field.

The spatial behavior of the willingness to pay for real estate products and the land prices are defined according to well established parameters. Both functions are expected to monotonically decrease with the distance from built environments. When they are explicitly calculated, simple gravitational functions are used.

Agent's behaviors are modeled according to plain prototypes. Planning boards define the spatial incidence of the characteristic time naively, implementing an anti-sprawl policy. Developers are profit-maximizing agents that are aware of the local conditions on any available parcel. When different developer's types are modeled (patient and impatient), there are defined according to different rates of risk-aversion.

The sub-center emergence studied using the models developed here is a direct consequence of these settings. Each one of them is a reasonable economic consideration and common-sense assumption about the behavior and the interactions between the different types of agents. Therefore, the explanation proposed here is based on sound foundations.

5.2. Further remarks

Following the research goals, the models developed here intend to contribute and expand the current knowledge in urban economics. This is the reason for the statement that any model developed in the context of this research proposal should be able, at least under specific settings, to reproduce the classical result of urban economics models – An Alonso-style mono-centric city with a monotonic decreasing willingness to pay function towards the edges, and monotonic decreasing building heights from the CBD outwards.

In the comparative static's models (papers 1 and 2) two simple conditions are enough to achieve this. First, the characteristic time must be constant along all the linear space. Second, both cities should be far enough to cause the willingness to pay in the hinterland between them to decrease to zero. In both cases (cities of comparable size and cities qualitatively different) the developer's choices under those conditions will reproduce mono-centric cities in the linear space edges.

As already mentioned in papers 3 and 4, a city in which homogeneous impatient developers are present, always result in emergence of a mono-centric city with declining building heights as distance from the CBD increases. In this case the model reaches quickly a stable equilibrium without any endogenous forces capable of pushing it away anywhere. In this case not only the city shape predicted by Alonso-type models is reached, but the final urban equilibrium too.

Differing from mainstream urban economic and most agent-based models that are mainly focused on the demand side of the urban markets, in this research both demand and supply are addressed simultaneously. Since the main driver of urban development in all the models are land developers, the focus is on the supply. In the comparative static's models the demand is implicitly present, assuming that a developer will be able to sell any real-state product. In the agent-based models, both supply (developers) and demand are explicitly modeled. This is done using a growing city population function, which in turns constitutes one of the sources of pressure on city authorities when developable land becomes scarce.

Although market equilibrium situations are assumed to be a possible outcome of the demand and supply interactions, the basic assumption of the models in developed is that, at least during long periods of time, the market is out of equilibrium.

In paper 1 a static approach is implemented. The question is which location a hypothetical profit-maximizing developer will choose for his next project. The paper shows how different urban policies can lead to different, sometimes unexpected, location choices.

Paper 2 builds on the same model, but extends it to the more realistic case of two neighbor cities of different size in a dynamic framework. It is accepted in advance that the final result in this model (the equilibrium stage) will be an urban continuum in which the small town becomes part of the big city, assuming a steady population growth. However, the main question addressed by the paper is how the spatial configuration will change during the long time between the initial setting and the equilibrium stage. The question becomes which zones within the linear space will be developed first, and in which order. In other words, how the regional urbanization dynamics looks like.

The agent-based model implements a framework in which the market reaches instantaneous equilibrium at each model step. Freezing the model in any particular step, it is possible to quantify accurately which are the economical and planning forces over each parcel. However, under those frozen conditions the agents who participate in the model make decisions that will influence the equilibrium of the next step. In that sense, opportunities for exceptional profits are created dynamically by the different actors participating in the model.

The models are not complicated, in two senses. First, they are mathematically tractable. In addition, a small set of well-defined agents with a clear agenda are enough to create the required outcomes.

The set of models developed here constitute a genuine contribution to the urban economics and urban dynamics scientific literature. The motivation for their development was the dissatisfaction from the existing urban economic models that try to explain the ubiquitous presence of poly-centric cities. The set of models are able to describe the mechanism underlying sub-center emergence in cities in a reliably and convincing manner. Urban dynamics and poly-centricity are being extensively studied in the last years, both under theoretical and empirical approaches. The set of models proposed here stands at the core research issues of several branches of urban economics and regional science and comprise a novel and original contribution in these fields.

6. Additional bibliography

The following bibliographical list includes only sources not cited in the papers presented. It is presented in addition to the bibliography chapters of each one of the papers included in Chapter 4 ("Findings").

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