Digital Phoenix Project: A Multidimensional Journey through Time

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Abstract

The Digital Phoenix Project is a multiyear project aimed at developing a realistic digital representation of the Phoenix metropolitan area through space and time that can be experienced in Arizona State University's Decision Theater. A significant objective of this project is to create an environment for querying, researching, and visualizing critical urban sustainability issues confronting a rapidly urbanizing area. By creating a multidimensional virtual model of Phoenix from a variety of data sources, we can visualize patterns of growth and development, as well as their consequences, emerging across the continuums of space and time. The modeling of future environments will enable the assessment of policy scenarios

and guide desired future urban-environmental patterns. A digitally constructed model of the city will also allow us to discover what Phoenix could have been like, starting with historical data as the basis for projecting to the present and into the future.

1. The Genesis of Digital Phoenix

The Digital Phoenix Project started in July 2006 with a grand vision of developing a digital representation of critical elements driving the evolution of the Phoenix metropolitan region. By digitally encoding important information about the past, present, and potential future of the metropolitan region, we hope to create a well-integrated experimental model that can be queried and visualized in a highly immersive environment like the Decision Theater at Arizona State University. The objective is to generate well-calibrated and realistic experimental models that can provide answers to questions such as: a) why and how the city developed in the manner it did, b) how the decisions we make today will shape future environments in this region; and c) what will be the sustainability implications of the future scenarios. In essence, we are attempting to build a tool for planning and decision-making that can be used by public officials, scholars, and citizens, to enable sustainable growth in this region.

We began the project by parsing the broad agenda into three component parts: 1) a digital 3-D parametric model of the current physical environment; 2) digital encoding of historical data on the physical and environmental evolution of metro Phoenix; and 3) an urban futures simulation engine that can provide scenarios of future land use, housing, travel, and employment patterns based on current trends and policy choices. While the three components listed above continue to be the primary branches of the Digital Phoenix tree, several other research efforts were also brought into the fold to resolve more fundamental issues tied to the objectives of the project. For example, we required spatial and non-spatial measures of sustainability to compare the various current and future developments (scenarios) in Phoenix. Also, the voluminous amounts of data and the corresponding high intensity of computation that is required necessitate high performance computing. We were fortunate to have the assistance of ASU's High Performance Computing group who helped in leveraging our computing power severalfold. In addition, a team of individuals at the Decision Theater has been critical to this endeavor given the ultimate objective of porting many of our products to the immersive environment offered by the Decision Theater. The integration of the various components of the Digital Phoenix Project is illustrated in fig. 1.

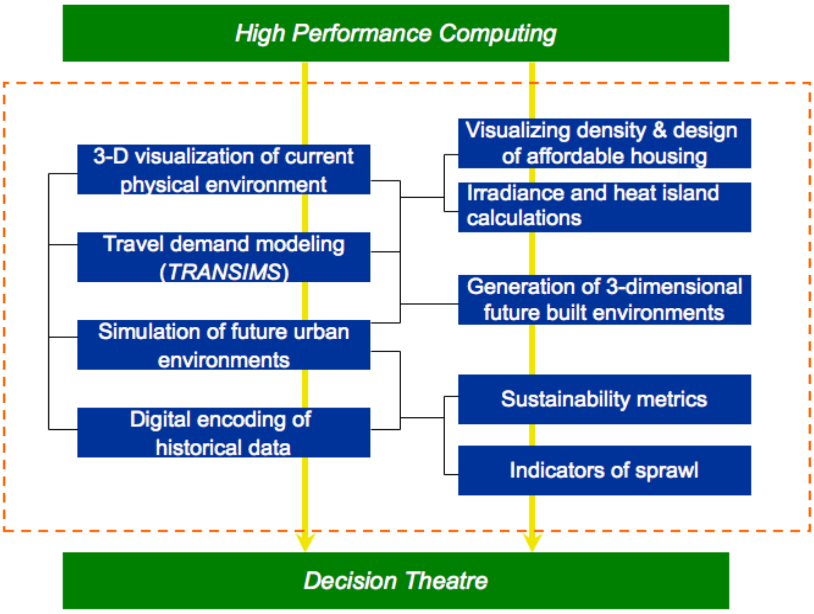


Fig. 1. Integration of the different components of Digital Phoenix Project

2. The Context

Human civilizations in central Arizona date back over 2000 years, although the current history of Phoenix starts sometime in the nineteenth century. The older civilizations were organized around water and other natural resources that were necessary for their survival. The modern city of Phoenix is also dependent on water and resources, although massive infrastructure and urban planning processes are necessary to support the population as the city grows. With growth comes increasing complexity and challenging decision-making regarding future urbanization. Economic development, a creative workforce, and technological innovation are critical assets in continuing the transformation of Phoenix into a more desirable city. The Digital Phoenix Project will create a visual planning tool with keen insight into urban dynamics in Phoenix through the use of state-of-the-art visualization, computation, and informatics tools, combined with detailed social, economic, and environmental data.

Rapid urbanization of the Phoenix metropolitan area has led to increasing pressures on the area's environment and infrastructure. Greater Phoenix is in the grip of explosive growth. The region's home county, Maricopa, sits atop the list in U.S. population growth from 1990 to 2000. The Phoenix-Mesa Metropolitan Statistical Area (MSA) ranked 5th in terms of absolute population growth in the U.S. over the same period, and 8th in percentage growth. The population build-up has even taken hold of smaller cities. Gilbert ranked 2nd in population increase across all U.S. incorporated places, with Chandler (9th) and Scottsdale (15th) following close behind (see fig. 2 for location map). According to unofficial projections, Phoenix is currently the fifth largest metropolitan region in the United States having surpassed Philadelphia sometime in 2005 (Wikipedia). Several of these cities, such as Paradise Valley and Sun City, are relatively small enclaves; others such as Phoenix, Mesa, and Scottsdale are large conurbations. Given the rate of growth and the diversity of settlements in terms of their history and socio-economic characteristics, the region is an archetype for studying the sustainability debate facing urban systems across North America. Indeed, Phoenix imports over one million acre-feet of water per year to support the population and its agricultural and industrial activities.

The metropolitan area consisting of Maricopa and Pinal counties spans a combined land area of 14,598 square miles for about 3.5 million inhabitants with a resulting population density of 184 persons/ sq-mile. Like most cities, the metropolitan region includes a textured surface of human demographics with regions of more and less affluence, age-distribution, population density, and occupational communities including many ethnic communities. These unique features make Phoenix an important city to explore because, in many ways, it is the first desert city to grow so quickly for so long to such a tremendous size. No other city in the U.S. is hotter, making Phoenix a prototype for studying rapid urbanization in desert regions, a trend that is occurring globally in other desert locales. Due to the rapid growth, the planning, development and management of infrastructure in Phoenix is complicated. Features of the city are changing so rapidly that unless a thorough documentation of the data-sources are captured during this transformation we will never have the opportunity to understand the successes and difficulties involved with building this metropolitan region.

The pressures of this explosive growth in the Phoenix metropolitan region are evident across various urban systems including transportation, water distribution, and temperature controls. The demands on urban infrastructure are growing disproportionately faster than the rate at which such infrastructure is being expanded. The environmental problems of air pollution, water availability, and land degradation, among others, are compounded by both the increasing demands on natural resources by the growing urban population and the inability to manage such population growth through the adequate provision of urban infrastructure (Guhathakurta 2003). What is needed is a new approach to urban planning, design, and environmental management. This approach should use the current methods and techniques, but also include modern technology and state-of-the-art science to create realistic and compelling models of urban features that can be explored interactively by planners and key decision-makers. Such tools will fundamentally change the way cities are designed and managed. This approach will also enable innovative thinking and rapid exploration of the connections between land, the environment, human behavior, and human settlements. It will also necessitate new tools and better theories to understand the dynamics of urban growth and change. These are the goals of the Digital Phoenix Project.

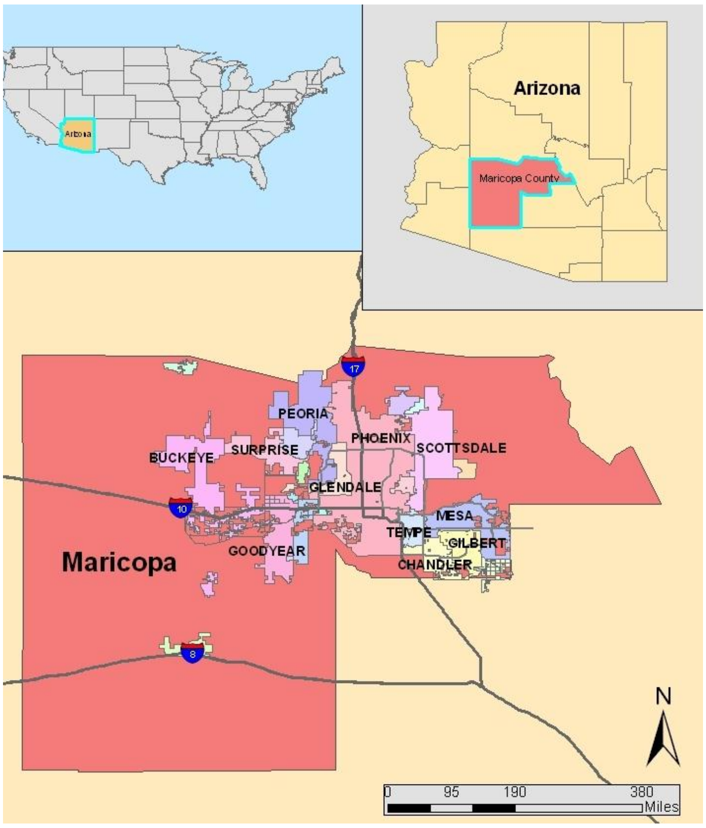
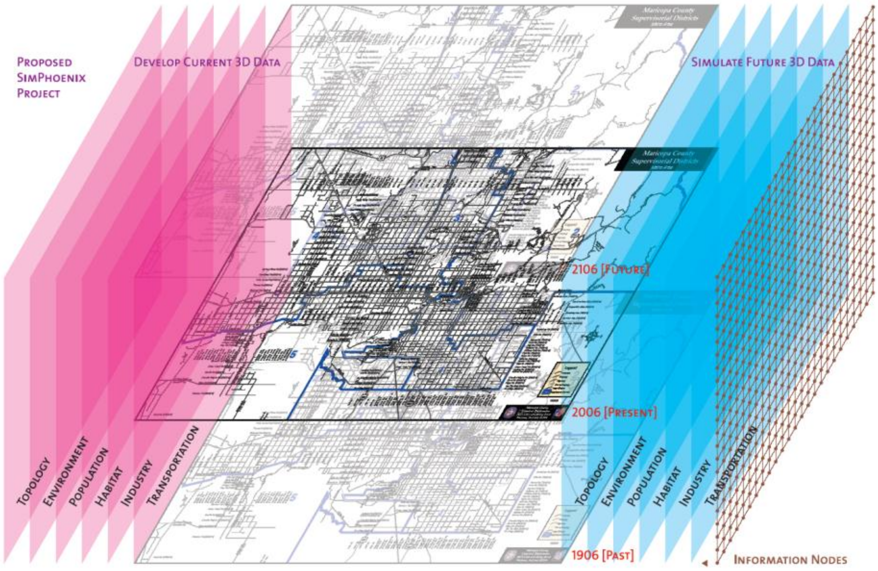


Fig. 2. Location map of cities in Maricopa County, Arizona

The development of visualization tools has several potential uses. For example, it would allow us to examine the factors that led to the city's development patterns based on historical information. The multilayered historical digital data will provide answers to several questions regarding "evolutionary trends" such as changes in land resulting from the loss of streetcars or from the advent of new technologies (e.g., air conditioning). Specific questions about influences on landscape patterns, household water use, and changing demands for energy and materials can also be examined using tools developed for Digital Phoenix. Further, simulation models of future growth in Phoenix can also offer important insights about desirable social behavior and policy choices. The Phoenix UrbanSim model will be able to evaluate questions such as: how will the future light rail transit system in the Phoenix metropolitan area affect the type and location of new housing? (a topic that will be discussed later in this article) where will the concentrations of jobs be located if Phoenix becomes a hub for biotechnology companies? what will the air quality in the metropolitan area be if automobile usage continues to increase at current rates? The answers to many of these questions require detailed information that is currently becoming available and will be brought together under this project. Most importantly, as this project matures, we will create a platform to share possible outcomes with key decision-makers, researchers, and the general public to support informed decision making about the future of Phoenix.

Throughout its history, Phoenix has undergone significant transformation in its structure and functions, and in its social, economic, and physical environment. This transformation, which up until now has been continuous in some respects and discrete in others, is impossible to predict from any point in the past. More recent research on cities as self-organizing, complex systems reinforces the fact that the future is not given and deterministic laws do not, by and large, govern the evolution of human habitation on this planet (Batty 2005; Beneson and Torrens 2004; Portugali 2000; Guhathakurta 2002). What we do know is that massive modern cities create planning challenges that require foresight into the possible consequences of current decisions. Cities are now being examined from the perspective of networked systems stretching in time and space. These networks evolve in dynamic, self-organizing ways, generating structure while at the same time breaking symmetries. We now know that there is no universal optimization principle for complex systems, like cities, but several possible futures that differ from each other qualitatively.

The core of the Digital Phoenix vision is a digital copy of the Phoenix metropolitan region in space and time that can be experienced in the Decision Theater and other richly textured immersive environments. Elements of this vision include a visualization component that would scale according to the users perspective and include large libraries of richly textured urban elements that can be combined to construct both local and regional urban environments. These environments would be amenable to visual exploration at different scales and perspectives with appropriate walk, drive, and fly-through digital techniques. The second component of the larger vision is to develop an engine to model and visualize both the past and the future using detailed data from historical and current social, physical, economic,



and environmental attributes. Different techniques are being used to project the future and the past. While future projections will use statistically calibrated, agent-based models of individual and social behavior across space and time, the reconstruction of past environments will be based on detailed archival analysis of several “layers” of data (see fig. 3). By creating a multidimensional representation of urban data, we will be able to visualize patterns that emerge in space and time. That is, one goal of the visualizations is to create realistic 3-D images of the city for navigation purposes, while other visualizations will reveal patterns of economic development through time. The ultimate longer-term objective is to bring together the modeling and richly textured visualization components so that we will be able to visualize within one environment, the past, the present, and the future. Hence we can recreate the evolution of Phoenix as a journey through time.

Fig. 3. Conceptualizing Digital Phoenix as a “journey through time”

3. Research Components and Methods

The project has three main components: the development of a digital representation of Phoenix in the present, historical records of Phoenix that can recreate the city at times in the past, and modeling tools and theories to generate future representations of Phoenix. All three components are ambitious in scope, but by integrating the three into a unified framework and leveraging the Decision Theater capabilities, the outcome promises to be a powerful tool for urban planning in Phoenix.

As we create the ability to digitally-document the present, we will also begin to use the information about the present to extend into the past and future. Historic records exist, but not in digital data formats because the technology was obviously not available. With the advent of computers, historical information is becoming more available in digital formats, but often important qualitative information and details that do not easily convert to digital formats are lost. This project aims to advance the digital archives of Phoenix's history and use the capabilities of visualization to move back in time and track its progression. We will create a digital past of Phoenix in such a way that the data is integrated with future information. We will also create a digital future from the data and the Phoenix UrbanSim implementation. This will generate future scenarios that allow the project to create virtual futures. The ability to move forward in time from current information will also generate the capability to move forward in time from past states. This capability will allow us to fill in the periods of time when limited records were available though theories of settlement and urbanization. It will also allow us to envision what the future might have been like if different decisions were made in the past.

The project has several components but the central core is comprised of a rich data base that scales up and down both in time and space. This data is then selectively extracted to develop multidimensional visualization of large regions as well as small neighborhoods. The data would also provide information about the evolution of various systems of social, physical, economic, and environmental networks over time in the Phoenix metropolitan area. This would allow the examination of the history of specific social habitation patterns, offer means of experiencing real time-immersive environments, and provide a means for evaluating future growth scenarios. Each of these endeavors would be developed concurrently in a manner such that they integrate across scales and times. The three components of this project are discussed below.

3.1. Visualization through immersive environments in real time

One of the most important aspects of visualizing scientific simulations of a city is the definition of 3-D data structure of the virtual city model. To date, no data format allows for a comprehensive picture of all urban processes. Nor do we expect that such a representation of reality can exist. However, the tools and technologies that we work with as part of our current research will allow for significant advances in capturing many of the fundamental processes that emerge in complex urban systems. Moreover, the creation of appropriate digital representation has tremendous value for pattern recognition, and for rapid theory testing and design, on a synthetic population whose basic actions are well-predicted at large scales. Having the basic data structures and initial set of real data is an incredibly powerful capability, but it is only the beginning of what is possible in large-scale urban simulation. Especially, in order to visualize the model for decision making in immersive VR (virtual reality) environments, the data structure should be designed to support various kinds of input data flexibly. For example, some decision makers may need to observe voting patterns from the current city model. Others may need to experiment with new buildings for landscape design evaluation.

In addition to the data structure issue, the city model must be visualized with enough impact for decision makers to explore new ideas and help deepen observation. Therefore, the city model should be created with textures and details.

There are many different methods for creating 3-D city models, and researchers are trying to develop more efficient and effective methods. These modeling methods are mainly categorized into three approaches; automatic, semi-automatic, and manual. The automatic approach is to extract 3-D objects such as buildings, streets, and trees from aerial or satellite images by using the technologies of image processing and pattern recognition in artificial intelligence. The semi-automatic approach is to create 3-D objects one-by-one with the support of technologies like photogrammetry and 3-D vision. The manual approach is to create all geometries of an object one-by-one in CAD and CG software packages that are commercially available such as 3-D Studio Max and Maya. Spine3D is one of the well-known CG design platforms that develop 3-D city models manually.

The methods of 3-D city modeling also vary according to the resources available and overall objectives of the project. LiDAR (light detection and ranging) and photogrammetry are the technologies commonly used in extracting 3-D geometries. The LiDAR instrument transmits light to a target and measures it by using the reflected signals. There are two approaches in using LiDAR. One is to acquire the LiDAR data from an airplane. This is commonly used in remote sensing for creating digital surface model (DSM) and digital terrain model (DTM). Another approach is to get the LiDAR data from the ground and extract the complicated geometries like architectural components and civil structure (Früh and Zakhor 2003). A set of points extracted from LiDAR is converted into polygons. This procedure makes it possible to obtain details, but it requires researchers to fly or walk over to get the necessary data.

Photogrammetry is another solution for extracting 3-D geometries. Like LiDAR, it can be used for both aerial and ground images. Aerial images are used to extract abstract forms of buildings, and the ground images are used to extract their details. Nverse Photo (www.precisionlightworks.com) and Shape Capture (www.shapecapture.com) are examples of commercial software packages for 3-D modeling that use photogrammetry. There are two approaches for photogrammetry. One is to use photos taken from the ground. An advantage of this approach is the relative low cost. On the other hand, there are some disadvantages. First, it is difficult to take photos of buildings from behind because of security and privacy issues. Second, since several photos are required to cover all elevations for each building, it is necessary to manage a number of image files. Third, it is difficult to match the images with different white balances on the same building. In short, the approach using ground photos is useful for extracting building geometries when details are required such as for SH and CH models, but this process requires more time to manage and fix the textures.

Yet another approach is to use aerial or satellite images. This process is sometimes advantageous because it requires only a few images. Since the textures of buildings are extracted from the same image, the color balances in the image are not an issue. However, a substantial disadvantage is the cost of this method; it costs more to take aerial photos than ground photos.

3.1.1. Classification of 3-D city models

Choosing the most suitable method for creating 3-D city models depends on the given resources and objectives. Table 1 illustrates one classification of 3-D city models based on quality and spatial scale.

Table 1. Classes of 3-D City Models

	Low Quality (Online Quality)	Middle Quality (PC Quality)	High Quality (Movie Quality)
Street Level	SL	SM	SH
Block Level	BL	BM	BH
City Level	CL	CM	CH

There are three scale categories: street level, block level, and city level. The street level model is used to visualize a street with buildings and landmarks (such as trees, traffic lights, signs, and bus stops) from a human perspective. The block level model visualizes street blocks in a city, including buildings and landmarks, from a bird's eye view. The city level model visualizes a whole city from several thousand feet above ground as from an airplane.

In addition to the classification based on scale, the 3-D city models are classified into three quality classes: low, middle, and high. The low quality model is designed to render interactively in real time on Internet browsers, the middle quality model is to render in real time on PCs, and the high quality model is not for interactive rendering but for static rendering.

The low quality street level model (SL) has buildings and landmark components without any textures or materials. This model is typically used for evaluating the height and volume of buildings from a human perspective. This method is often applied at the beginning phase of design in architectural design studios. The model is created with commercial 3-D computer graphics software packages such as FormZ (www.formz.com) and SketchUp (www.sketchup.com).

- The middle quality street level model (SM) has more details and textures than SL. Many 3-D games such as DOOM3 (www.doom3.com) is classified in this category. In order to visualize the model interactively in real time, the details are created with minimum polygons. With the improvement in graphics card technologies, very realistic images can be rendered with high-resolution textures.
- The high quality street level model (SH) is the highest quality model and is seen in architectural presentations and Hollywood movies. Since it is necessary to create 3-D objects one-by-one using computer graphics (CG) packages, it takes a lot of time and effort. The images are very realistic and beautiful, but it cannot be rendered in real time.
- The low quality block level model (BL) is used for visualizing street blocks in a city. Since a model usually has many buildings, each building is a simple volume without any textures in order to render them in real time. Google earth is one example that shows this model in 3-D views (http://earth.google.com/). 3-D-GIS models with digital terrain model (DTM) and 3-D buildings, which are created by extruding 2D polygons with building height values, is classified in this category as well.
- The middle quality block level model (BM) is an upgraded form of BL with textures for buildings and ground. The ground object has textures based on ortho-images. Many automatic approaches have been re-

searched and developed for creating models in this class using photogrammetry and image processing technologies (Pennington and Hochart 2004).

- The high quality block level model (BH) is based on BM, but with more details added to each building. The model is usually employed for static rendering because it is too computing-intensive to render the model interactively in real time. A model of 1930s New York City used in the Hollywood movie *King Kong* is an example of this class.
- The low quality city level model (CL) shows only DTM mapped with ortho-image without buildings, street, or landmarks.
- The middle quality city level model (CM) has DTM and buildings without textures. Each building is represented as a box.
- The high quality city level model (CH) has DTM and buildings with textures. These are extremely difficult to render in real time without scaling (i. e., changing the quality of resolution according to scale).

3.1.2. Creating 3-D models of downtown Phoenix

In this project, we adopted the method of creating 3-D city models from aerial photos using photogrammetry. This approach is chosen because it allows the development of a model that can be used in eight classes described in Table 1 (SL, SM, BL, BM, BH, CL, CM, and CH). This approach is also less time-consuming than the other approaches discussed.

The processes of taking aerial photos, scanning images, extracting buildings from the images, and editing 3-D objects are explained below.

Aerial photo and scanning The most important step in creating 3-D city models from aerial photos is to acquire high quality images in order to extract the textures of buildings.

In this project, several different kinds of aerial photography techniques were investigated. Two different cameras were tested. One was Canon Eos-1Ds Mark-II, which is capable of taking the highest resolution image among the digital cameras commercially available. The images were shot from an altitude of 6000 ft by airplane and from 2000 ft by helicopter. During the flight, an aerial photographer held the camera and took images manually.

In addition to the Canon Eos-1Ds Mark-II, a regular aerial photo camera for 9”x9” negative films was used to take the photos from 6000 ft and from 10,000 ft. The camera was fixed on the airplane and a pilot released the shutter.

As explained in Table 2 below, the image taken from 6000 ft using the regular aerial photo camera was the best for this project. The other images did not provide adequate details because the side images of buildings were not clear enough to detect building textures.

In order to get clearer images of the textures of the sides of buildings, it is necessary to take several oblique shots in addition to the vertical shots. The flight path for taking regular stereo-pair aerial photos is usually straight, as shown in the left image of fig. 4. However, in order to take several oblique shots of the same target, the airplane needs to fly over the same position repeatedly as shown in the right image of fig. 4. In addition, the pilot needs to release the shutter for each shot looking at the screen monitor in order to check the position of target in the image, and the photos are taken during a circular flight. The pilot needs to be skilled in order to get the proper oblique aerial photos. Three flights were required for this project since the first two failed because of an inexperienced pilot.

Each aerial photo is scanned at 2000 dpi resolution, and saved as TIF formatted image without any compression. Each scanned image has about 18,000 x 18,000 pixels as shown in fig. 5.

Table 2. Choosing appropriate aerial photographs

	6000 ft Film	10,000 ft Film	6000 ft Digital	2000ft Digital (Helicopter)
Pros	Best quality	Cover 3x 3 miles	Easy shot	Easy shot
Cons	Need an expert pilot	Low quality	Blurry images	Blurry images Many images

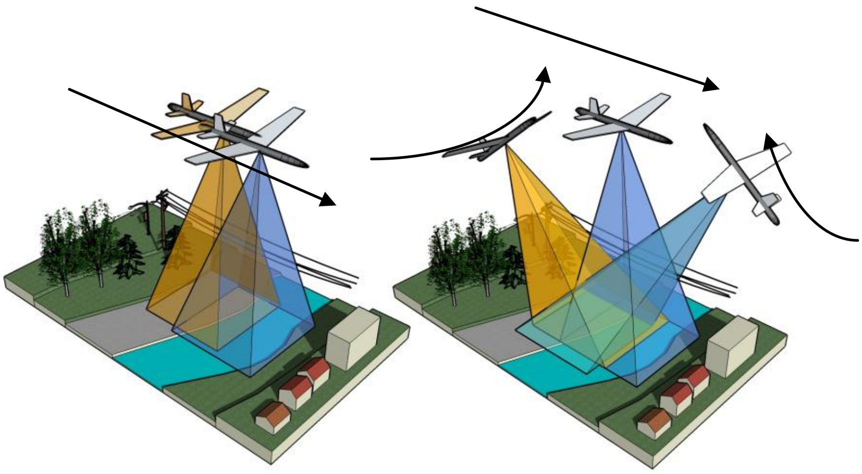


Fig. 4. Flight path for stereo shots

Fig. 5. Aerial images scanned at 2000 dpi

Modeling process. Nverse-Photo 2.7 (www.precisionlightworks.com), one of the commercial off-the-shelf photogrammetry tools, is used to extract 3-D buildings and the ground from aerial images. First, the following camera parameters are defined for stereo matching: 1) calibration focal length = 152.884 mm, 2) lens distortion is input as

$$K_0 = -0.2877 \text{ x } 10^{-6}, K_1 = 0.8168 \text{ x } 10^{-8}, K_2 = -0.4265 \text{ x } 10^{-22} \quad K_3, K_4 = 0.0000$$

3) the scanning resolution is set at 2000 dpi; and 4) X and Y offsets are defined using fiducial marks.

Once camera registration is done for all aerial images, the stereo matching process progresses smoothly. After the matching process, each building is created by drawing polygons on all images. For example, a polygon is created in the first image, and it is sent to the second image. The user needs to edit the polygon in the second image corresponding to the building. This process defines the height and form of the building. By repeating this process, the geometries of buildings are defined, and the textures of building are automatically assigned from different parts of aerial images. The ground is defined by inputting the ground truth points with the information of latitude and longitude instead of polygons. The texture for ground is also generated automatically.

The model is saved as a 3DS formatted file, which is one of the most common 3-D formats. In order to visualize the model at 3-D stereo theater, the model is converted from 3DS format to OSG (http://www.openscenegraph.org/) format. Fig. 6 shows the workflow of this project.

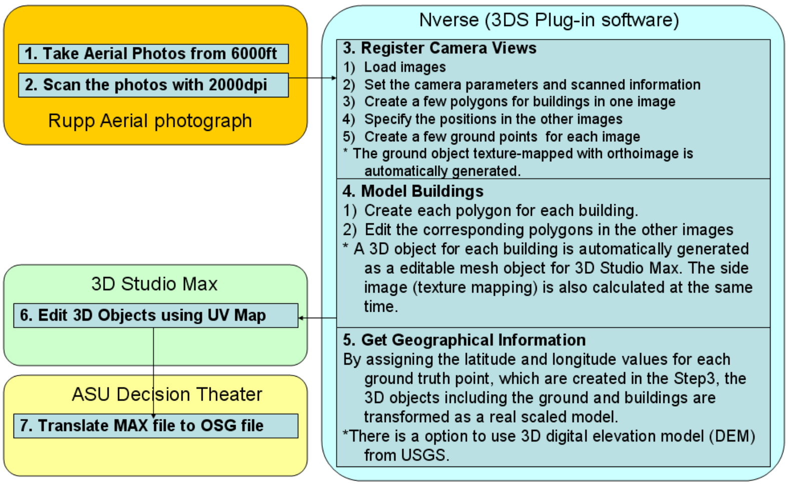


Fig. 6. The Modeling Process

Editing 3-D model. Autodesk 3D Studio Max is a professional 3-D computer graphics modeling and rendering package. The package is used for editing the buildings when they have some problems regarding their textures. If some parts of buildings are not visible in some images, the textures are distorted or not generated. In such cases the images taken from the ground can be used to fix the problems. UV-mapping, which is one of the most advanced techniques commonly used in developing 3-D games, is applied to edit the side images of buildings as shown in fig. 7. This process is tedious because it takes a few hours to fix the problems on each building.

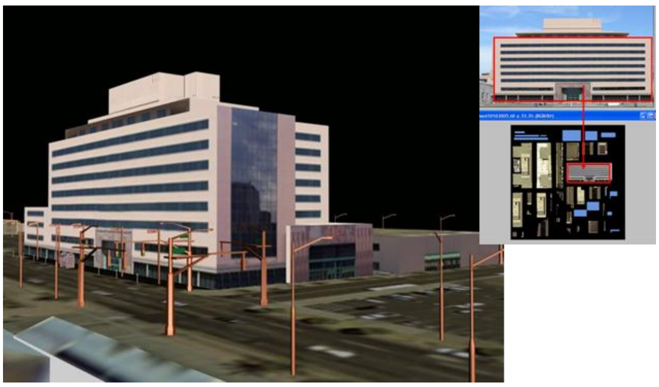


Fig. 7. Editing buildings

3.1.3. Results and application

Fig. 8 shows the model created in this project. The model covers about one square mile (1.6 km x 1.6 km) area in the center of downtown Phoenix with more than 700 buildings. The model was created within 16 hours by one person.

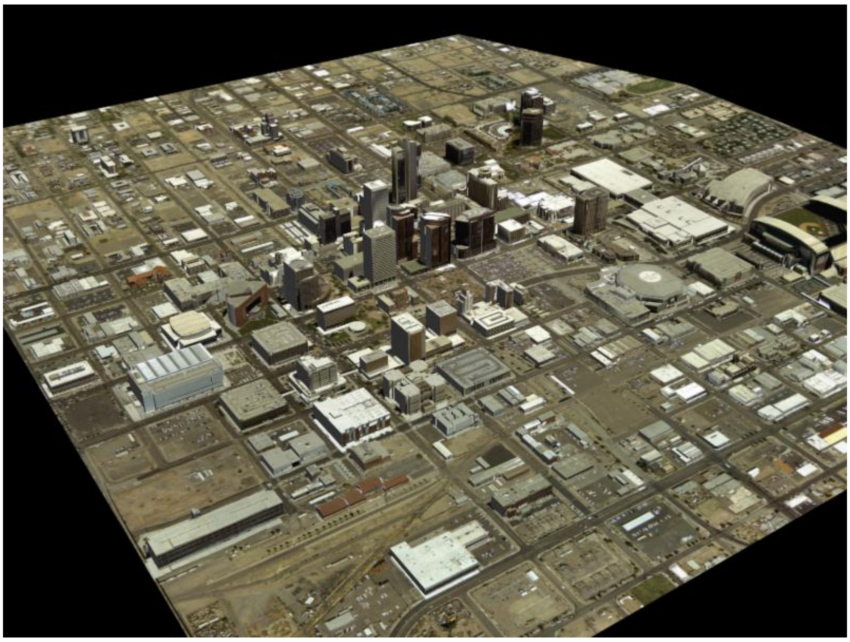


Fig. 8. 3-D city model of downtown Phoenix

Application of 3-D city model in Digital Phoenix Project. The Digital Phoenix Project is developing a 3-D immersive model of Phoenix's built environment on a UC-Win/Road platform (http://www.forum8.co.nz/index.php/eng/home). The immersive environment is specifically designed for Arizona State University's Decision Theater. This model currently comprises the one-mile square section of the downtown area (shown in fig. 8), which has been detailed with appropriate textures, street furniture, and signs, together with drive-through capability (see fig. 9). The transportation infrastructure of Maricopa County is now being imported to the platform for tying together sections of the built environment that have already been constructed in UC-Win/road or are in that process. The transportation infrastructure will also articulate with TransSims, traffic simulation package to provide accurate traffic counts at specific time of day during the week. By populating the virtual downtown environment with appropriate traffic counts, we will be able to offer realistic experiences of navigating through traffic at various times during the day. This will offer excellent first-hand knowledge of the subjective experiences of drivers and pedestrians in the Phoenix downtown area.

Other Applications of 3-D models. Four other applications that used the 3-D city model of downtown Phoenix are shown in fig. 10. The top left image (10a) shows the online web 3-D application using this model (www.ruthron.com/purl). The user can change the views and get the information of buildings on Internet browsers. The bottom left image (10b) demonstrates the application of 3-D printing. By using the device to get the XYZ position on the physical model, the building information is displayed. The top right image (10c) is the conceptual image to integrate the applications 10a and 10b with a big 1/32” scaled physical model. The bottom right image (10d) depicts a viewing of the 3-D city model in a VR environment.

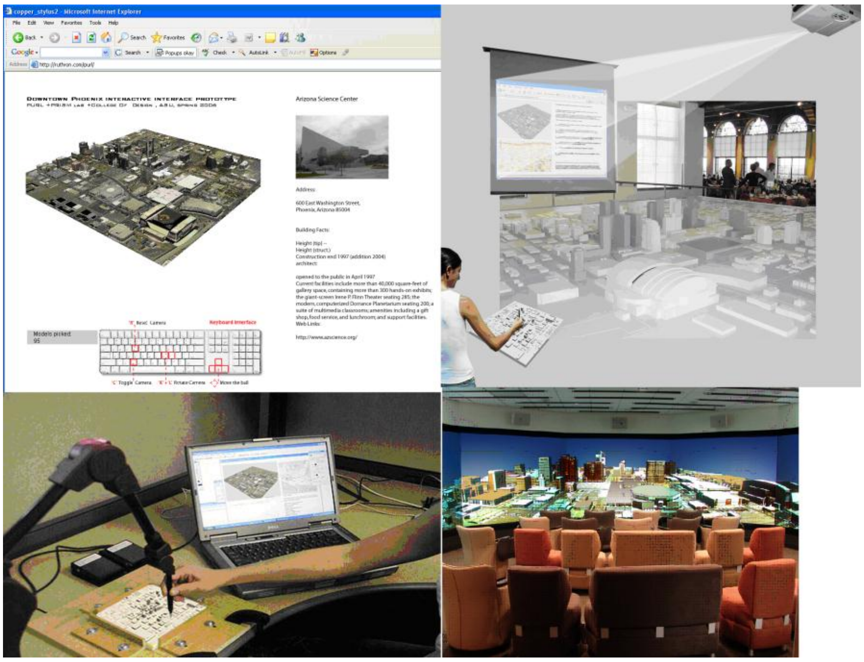


Fig. 10. Application of 3-D city mode: 10a (top left) online application; 10b (bottom left) tangible interface; 10c (top right) physical model; 10d (bottom right) VR model

3.2. Modeling of Phoenix Urban Futures

An important component of the Digital Phoenix Project is the ability to model and visualize alternative futures of Phoenix-based on different choices made about policies, regulations, and lifestyles. The simulation of future developments and their implications for environmental conditions and resource availability offers critical insights into how the future will unfold based on choices made today. Over the past several years we have implemented a modeling environment called UrbanSim, which is under active development at the University of Washington at Seattle. UrbanSim is probably the only large-scale agent-based model that has been successfully tested and implemented by regional and academic communities, which simulates future urban growth at a fine-grained spatial scale. We currently have a model of Maricopa County at a spatial resolution of one mile (Joshi et al. 2006). We are also implementing another version of the model at a spatial resolution of 150 meters.

3.2.1. Policy analysis using UrbanSim

The Central Phoenix/East Valley Light Rail Transit Project, which is now under construction, will provide convenient and comfortable transportation between Phoenix's central business district, the Sky Harbor International Airport, Arizona State University, several community college campuses, and event venues that currently draw about 12 million people each year from the region. The first phase of the project will include a 20.3-mile line that connects significant destinations in three cities – Phoenix, Tempe, and Mesa. It is expected that this phase of the project will be completed by 2008. In light of the new transportation option that will become a reality in less than three years, planners in the three cities are actively engaged in planning and redesigning the areas around the transit stops. The scenarios tested in this study takes into account many of the planned interventions around the transit stations, mostly in terms of introducing mixed-use and higher density developments. Fig. 11 shows a map of the overall planned system in relation to the various cities in the Phoenix metropolitan area.

The first phase of the Phoenix Light Rail project will include 32 transit stations within the cities of Phoenix, Tempe, and Mesa. These station areas are shown in fig. 3. Given that transit stops are designed to be closer together than the one-mile grid used in the UrbanSim model, we have allocated three analysis zones each having distinct characteristics. Zone 1 radiates north from downtown Phoenix and includes most of the downtown business district and the uptown arts district. This region includes some of the oldest neighborhoods in this metropolitan region and a fairly large

Fig. 11. Alignment of proposed Phoenix Light Rail

downtown core. Zone 2 is currently a low density corridor that is adjacent to the commercial airport and includes many industries that have located to take advantage of proximity to the airport. This corridor also includes several low-income neighborhoods and areas with a high concentration of minorities. Zone 3 is dominated by Arizona State University and activities supporting the university clientele. The concentration of student housing is high in this area. This zone also includes several ethnic retail establishments catering to a large international student community attending Arizona State University. The following analysis compares the transition of households in the three delineated zones based on scenarios with and without light rail transit for year 2015.

The scenario for different levels of transit usage was generated by changing modal split for all the transport analysis zones (TAZs) that include the 32 stations mentioned earlier. Accessibilities were recalculated such that for the 5 percent scenario, 5 percent of the total number of trips was added to transit and subtracted from auto. Similar procedure of increasing transit ridership was adapted for 15 percent and 25 percent scenarios. These scenarios were tested against "no build," where light rail is not built and the existing mode split continues into the future. Also, cities will be rezoning the station areas for high density, mixed-use developments. To account for this land-use change, development types of the gridcells falling under stations have been changed to high density and mixed-use development type. The particular light rail scenario discussed below assumes the mid-range of the three scenarios tested, that is, 15 percent of trips to and from the areas adjacent to light rail will be on the proposed Phoenix Light Rail system.

Implementing UrbanSim: data, process, and validation. UrbanSim is not a single model. It is an urban simulation system, which consists of a family of models interacting with each other, not directly, but through a common database. There are seven different models within UrbanSim

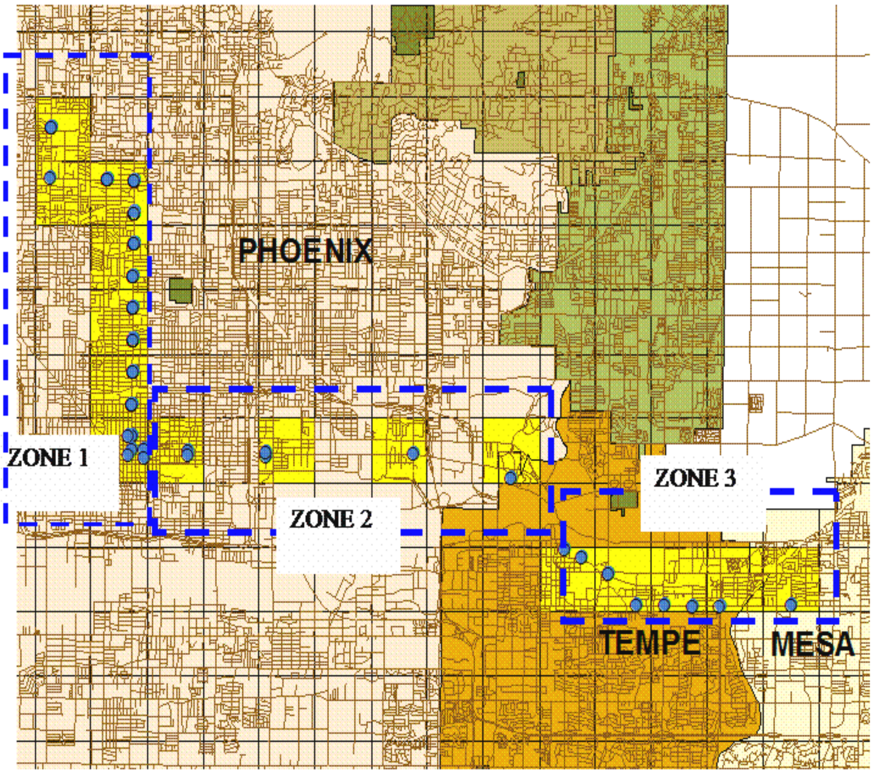


Fig. 12. Delineation of zones for study of light rail impacts on

(economic transition model, demographic transition model, employment and household mobility models, employment and household location choice models, household mobility model and the real estate development model). A more detailed description of each of these models and their underlying theories are available at (http://www.urbansim.org/index.shtml). Here we discuss the specific implementation of UrbanSim for Maricopa County, completed at a spatial resolution of one mile, and its application in evaluating one scenario of future land use and household type changes resulting from a proposed light rail system.

Data. The input data included in the data store consists of parcel file information from the county assessor's office, employment data from Maricopa Association of Governments (MAG), census data, detailed land use and land valuation data, boundary layers showing environmental, political and planning boundaries (also from MAG) and a chronological list of development events. A set of software tools such as ArcGIS and MySQL was used to extract the data from input files, calculate values and construct the model database in the specified format.

The data store contains all households in Maricopa County starting with the base year 1990. Each household is a separate entry in the households table with associated characteristics such as household income, size, age of head of household, presence and number of children, number of workers, and the number of cars. In addition, the data store contains every job present in the Maricopa County by location (i.e., grid id), job sector, and whether the job is home-based or not. Altogether UrbanSim requires about 60 data tables, which are used in the complete database. Each table has a well-defined structure. The model components include a script to check consistency of tables, which when run provides warnings and error messages if any table is incorrectly formatted for UrbanSim.

The process of creating the Maricopa County database for UrbanSim required the following steps:

1. Define project boundary (Maricopa County)
2. Define the base year for data (we used 1990)
3. Generate grid (9511 grid cells, one-mile by one-mile each, were generated for Maricopa County)
4. Assign unique IDs to grid
5. GIS Overlays: Parcels on grid; transportation analysis zones (TAZ) on grid
6. Allocate parcel characteristics to grid
7. Assign employment to grid
8. Reconcile non-residential space and jobs
9. Synthesize households and locate them by Grid ID
10. Generate diagnostics and resolve inconsistencies
11. Assign development types

12. Convert environmental features to grid
13. Convert planning boundaries to grid
14. Load database into MySQL
15. Run consistency checker

In this paper, we do not attempt to describe each of these steps in detail but the steps are well documented in the UrbanSim manual available at www.urbansim.org. There is however one step, step 9 above, that requires special attention given that it is an extraordinary process when compared to most land-use projection models. As mentioned earlier, UrbanSim database requires information for every household in Maricopa County by their special attributes. There is no single source from which this entire data can be obtained. For this reason, UrbanSim provides a utility called the Household Synthesis Utility. As its name suggests this utility synthesizes the household data with the help of an *iterative proportional fitting algorithm*. The utility synthesizes households separately by family type for each Public Use Micro Area (PUMA) at the level of the block groups. Data sources required for the household synthesis utility are: 1) Sample of households by age of head, income, race, workers, number of children, and number of cars for families as well as non-families at the level of PUMAs from 5 percent Public-Use Micro-data; and 2) block group level data for the marginal distribution tables from U.S. Census Summary Tape file STF-3A. The algorithm iteratively matches the marginal totals at the level of block groups to varying sets of households represented in the 5 percent PUMS sample. When a selected set of households match closely the aggregate block group statistics, that household set is assumed to belong in that block group. Subsequently, households in the block groups are associated with the grids-IDs. In this manner the households table is populated and the synthetic process of household allocation closely approximates actual household locations.

Another important aspect of this modeling approach is the use of accessibilities as a critical driver of jobs and household locations. The information about trips between TAZs in Maricopa County at various points in time was obtained from Maricopa Association of Governments (MAG). This data allowed us to calculate logsums by travel mode from which accessibilities were derived for incorporation into UrbanSim data store. UrbanSim is usually run in tandem with an external travel model, so that the accessibilities can be updated at regular intervals. For our purposes we used three sets of accessibilities (1993, 1998, and 2008) based on the output from the travel model used by MAG.

Model estimation and validation. Given that UrbanSim is actually a group of models that communicate with each other through a data store, the estimation process involves separate calibration of each individual model. Most of the models are of a “discrete choice” nature and are estimated through nested logit regressions (e.g., household location choice model, developer choice model, and employment location choice model). The land price model is different from the previous set since it is the only model that is estimated through a linear regression procedure. The model parameters are derived with the help of external packages such as Limdep and SPSS.

Using the estimated parameters, two model configuration tables were generated for each model -- the model specification table, and the model coefficient table. These tables are usually the last tables to be generated. Once these tables are populated with appropriate parameters, UrbanSim model runs can be accomplished. Fig. 1 provides the 1990 and 2015 household location results for one UrbanSim run using the “business as usual” scenario.

Model validation is a crucial process for building confidence in the modeling results. For this paper, UrbanSim model is run from 1990 through 2000 and the simulated results are compared to the observed data to check the validity of the model. Practical constraints on creation of historical data for use in validation often preclude the feasibility of historical validation of this sort, but this remains one of the most informative ways to assess the model before putting it into operational use. The simulation results are compared to observed data at two units of geography. As seen in table 3, the correlation between the simulated and observed is close to 80 percent at the level of the grid cell. However, this correlation is lower when a larger unit of geography such as the transportation analysis zone is considered.

Table 3. Correlation of Simulated to Observed 2000 Values

	Cell	TAZ
Employment	0.8	0.71
Households	0.76	0.66
Housing Units	0.79	0.64

Analysis of UrbanSim Scenarios with and without light rail. The introduction of light rail in the Phoenix metropolitan area seems to increase the number of households in zones 1 and 2 when compared to a future without light rail. Between 2008 and 2015 the number of households in zones 1 and 2 increased 19 percent and 15 percent without light rail, respectively. Zone 3 also registers an increase in the number of households in this scenario by 6 percent. In contrast, the scenario with light rail assigns very slight changes to household numbers in zone 1, but significant increases in zone 2. The number of zone 2 households increases by 12 percentage points during that same period when compared to no light rail scenario. Figs. 14 and 15 show the change in households by year for the two scenarios described above.

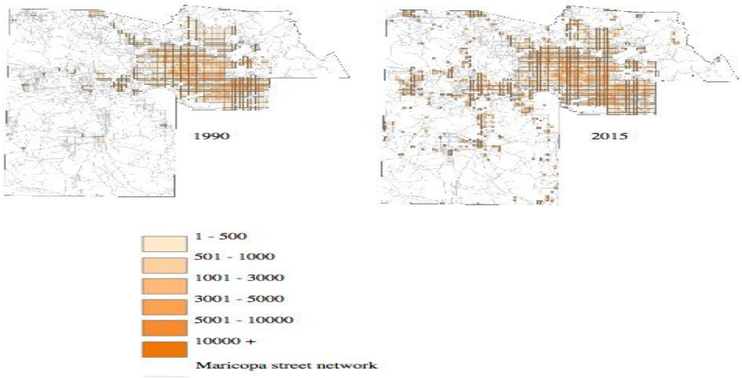


Fig. 13. Household simulation using "business as usual" scenario

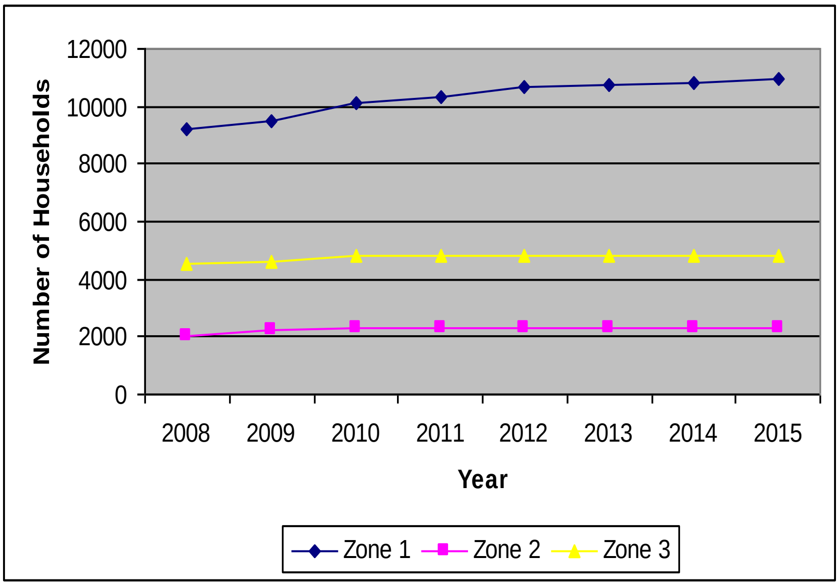


Fig. 14. Change in number of households by zone without light rail

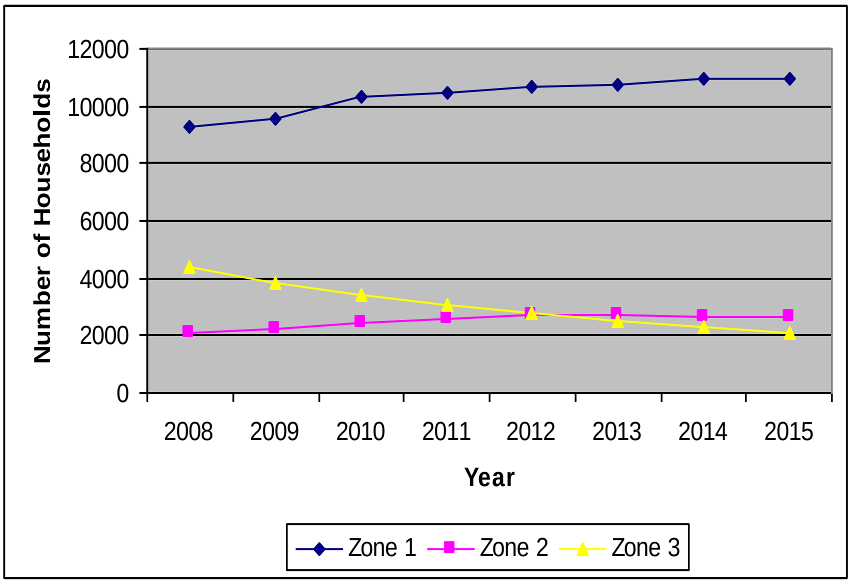


Fig. 15. Change in number of households by zone with light rail

Household transition due to light rail. Characteristics of households in the three zones show different trends based on scenarios with and without the introduction of light rail transit in 2008. In this paper we report on two of the important characteristics of projected future households adjacent to light rail station areas income and race.

The three zones delineated for the study include, on average, low- to moderate-income households and the "no build" scenario does not change that overall character. Under the "no build" scenario, zone 1 registers the highest income of the three zones during the period of projection. Zone 2 remains the lowest in terms of average household incomes of the three zones. Both zones 1 and 2 show slight declines in real average incomes over the seven-year period of projection. Zone 3, however, registers significant decline in real average household income of about 8 percent during this period. This result changes dramatically in the scenario with light rail, especially for zone 3.

The scenario with light rail has significant yet differential impacts on zone 1 and zone 3. Households in zone 2, in contrast, are less likely to be of a different income group with or without light rail. Average household income in zone 1 is projected to decline significantly in the seven years after the initiation of light rail transit. In contrast, zone 3, which includes the student community around Arizona State University, is projected to scale up in average income levels during the same period. While households in zone 1 remain the highest in average incomes of the three zones without light rail, they give up that top position to households in zone 3 when light rail is introduced. Zone 2 households remain at the bottom in average income in either scenario.

With changes in household incomes, the racial ethnic composition of the households in the three zones also changes depending upon the introduction of light rail. In all but one scenario, the percentage of white households (as determined by the racial attribute of the head of household) decline from 2008 to 2015. White households comprise about 72 percent of all households in zones 1 and 2, and 64 percent in zone 3 in 2008. In the scenario without light rail, the highest decline in the percentage of white households is in zone 2 (6 percentage points) followed by zone 1 (3 percentage points) and zone 3 (1 percentage point). This decline is almost entirely at the expense of percentage growth of households in the “other” racial category. The “other” category is a residual category used in the U.S. Census for those individuals who do not choose among the dominant racial categories for various reasons including unwillingness to disclose or being of mixed races.

The racial make-up of the three zones seems to be very different in the scenario with light rail than the previous scenario. The decline of white households in zone 1 is now more pronounced (10 percentage points). However in zone 2, which had the largest decline of white households in the previous scenario, the percentage of white households now decline by only 4 percentage points. More surprisingly, percentage of white households in zone 3 actually trend up in the scenario with light rail by a significant 6 percentage points. In essence, zone 3 will be the most impacted area with the introduction of light rail partly due to gentrification.

3.2.2. The final analysis

The scenarios evaluated to test the impact of light rail on adjacent neighborhoods in the Phoenix metropolitan area show different impacts in different zones. The findings are mostly in line with the literature on transit and land use connections but also add some surprising caveats to this literature. While, as expected, zones 1 and 2 register slight increases in residential density over seven years since introducing light rail, household densities in zone 3 actually decline under this scenario. This result can be explained in light of current characteristics of zone 3 and its unique location. The household density in zone 3 is already among the highest in the state and includes a high percentage of student households. Given the income profile of this young student population, the housing available is mostly rental, aimed at low- to mid-market clients. In addition, this area is among the most “jobs rich” areas in the state being close to the fourth largest university in the U.S. and to downtown Tempe. Therefore, the perceived accessibility of this area is already high and the introduction of light rail transit provides the additional amenity that would make it more desirable to up-market clients.

The projected gentrification of zone 3 is especially unwelcome for the student population who would be gradually pushed out to areas farther from the university. Given this possible scenario, both the city of Tempe and Arizona State University will have to plan ahead for more affordable student housing in the future. The university has already embarked on an extended plan to increase on-campus student housing. The city also needs to closely monitor land use changes and real estate values in zone 3 and look for innovative approaches for developing as well as keeping affordable housing. Regardless, this area seems to be ripe for redevelopment and the introduction of light rail will perhaps jump start the process.

An important caveat to keep in mind is that simulation models are useful tools for understanding the interaction of contextual elements and decision-agents but they are limited in their capacity to anticipate processes that have no antecedents. This limitation is more pronounced in very long-range projections. The simulation results reported in this paper is well within the period in which projections can be justifiably made, given well verified models. However, the results should be treated as informational and not definitive since human social behavior changes through time due to adaptation and learning. Regardless, planning for the future requires us to anticipate it and the careful use of simulation and/or modeling tools is indispensable for this endeavor.

4. Next steps

The challenge of the Digital Phoenix Project is to provide an integrated set of decision-making and visualization tools that will allow us to explore various options for developing the built environment in the Phoenix metropolitan area. In addition, these tools will address a range of research and policy questions about how the decisions we make now with regards to transportation options, land-use classifications, building designs, and urban landscapes among others will affect the future livability of this region. The project is unprecedented in scope and will undoubtedly offer several technical and theoretical challenges. The strategy so far has been to develop some strong expertise in a few areas in which there has been prior activity and some track record. By building upon existing research, we improve the viability of the project at least in terms of short-term deliverables. Regardless, the real contribution of the Digital Phoenix Project will be the integration of various disciplinary tools and theoretical frameworks in a manner such that policy and research questions that are transdisciplinary in scope can be addressed. This will be a significant contribution to scholarship as well as a critical and novel tool for decision making.

The team is focused on these integrative efforts, while, at the same time, developing expertise in specific tools and approaches. Given the long-term horizon, we have been ambitious and bold in our objectives. Regardless, we are aware of the importance of short term products to generate interest and visibility. We intend to create both.

We are embarking on several projects that will bring many of the project teams together to solve distinct problems. For example, the teams working on sustainability metrics and indicators of sprawl will engage with the team collating historical data about the evolution of Phoenix to provide sustainability indicators not just of the present and future scenarios but also of the past. Similarly, the team working on virtual reality engines of current downtown environment is being supported by travel demand models, which also provides critical information for urban simulation. Another project that has serious research challenges is developing 3-D visualizations of future scenarios that are typically mapped in 2-D space. We are undertaking research to develop algorithms for generating 3-D future virtual environments. We are also beginning to address questions at the neighborhood scale. One of the recent projects we have identified is the visualization of alternative design and density solutions for affordable housing. This project has immediate application to community decision making in a Decision Theater environment. Yet another project evaluates the consequences for energy use and heat island effects for different built environments. In essence, we have been able to attract new ideas and new contributions within our overarching vision for the Digital Phoenix project. Within the next year, we expect to make significant contributions to the knowledge of and tools for visualizing sustainable future environments.

References

Batty M (2005) Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals. MIT Press, Cambridge, MA

Benenson I, Torrens P (2004) Geosimulation: automata-based modeling of urban phenomena, Wiley, Hoboken, NJ

Früh C, Zakhor A (2003) Constructing 3D city models by merging ground-based and airborne views. Proc. of Computer Vision and Pattern Recognition, Vol. 2, June

Guhathakurta S (2002) Urban modeling as storytelling: using simulation models as a narrative. Environment and Planning B 29:895–911

Guhathakurta S (2003) Integrated urban and environmental models: a survey of current applications and research, Springer, Heidelberg

Joshi H, Guhathakurta S, Konjevod G, Crittenden J, Li K (2006). Assessment of impacts of the light rail on urban growth in the Phoenix metropolitan region using UrbanSim modeling environment. Journal of Urban Technology 13 (2):91–111

Portugali J (2000) Self-organization and the city. Springer, Heidelberg

Waddell P (2002) UrbanSim: modeling urban development for land use, transportation and environmental planning. Journal of the American Planning Association 68 (3):297–314