The Transformation of Economic Structure and its Environmental Implications for a Digital City: An Input-output Analysis for Austin, Texas*

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Introduction and Research Background

Since the publication of Manuel Castells' (1989) "*The Informational City*," over the past 15 years urban scholars have increasingly paid attention to the role of information and communication technologies (ICT) on urban development (Graham 2004).A new form of city -- digital cities in the space of electronic information flows -- has emerged to rival physical cities that have existed since the dawn of civilization. Although scholars from various academic disciplines interpret the concept of digital cities differently (Mitchell 1995; Rupprecht Consult 1998; Horan 2000; Ishida 2000; Batty 2001; Goodchild 2001), they generally agree that ICT has become the backbone and penetrated into almost all major aspects of urban life in digital cities (Ishida and Isbister 2000; McCullough 2004).Computers were first introduced as a tool to study cities in the late.1950s, but with the emer-

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gence of digital cities by the late 1990s, computers became an integral part of the city we were studying using the very same computers (Sui 1997; Mitchell 1999, 2004).ICT technologies have altered the spatial and temporal types of urban life in many fundamental ways as they emerge as an integral part of global network of productions in many cities (Roper and Grimes 2004).The traditional, real cities with spatial agglomeration of both commercial and non-commercial activities annihilate time by space via the morphology of the compact city whereas digital, virtual cities are characterized by the annihilation of space by time via a much more decentralized urban form knitted together by ICT technologies (Graham and Marvin 1996). The rapid transformation of cities by ICT technology has resulted in a global urban splinterism (Graham 2000; Graham and Marvin 2001) with far-reaching consequences in multiple domains.

Couleclis (2004) argues that the concept of digital cities is a multilayered identity that can be understood as the intersection of three domains: a physical urban area, urban population, and network society (Figure 1). She further calls for more thorough studies on digital cities from ideological, technological and social perspectives. Couleclis's work has set out a useful road map for the construction of digital cities. What is missing in her proposal though, are the environmental consequences of the emerging digital cities. For example, how will ICT technologies affect the material and energy flows within a city and between cities? Is E-commerce environmentally friendly? How will the physical urban morphology evolve with the emergence and maturity of digital cities? Will cities in the digital age continue to sprawl or become more compact?

The social, economic, and environmental implications of the digital city have been widely debated in the literature (Gelernter 1991; Tanabe et al 2002; Couclelis 2004). Among various statements made about digital cities, perhaps the one that has the most direct policy implication is the argument that digital cities can serve as models for sustainable development due to ICT's great potential to substitute information for material and energy consumption, thus ameliorating negative environmental impacts (Sui and Rejeski 2002). However, there is a general lack of empirical studies testing the validity of this argument.

With regard to the environmental implications of digital cities, three major arguments have been made in the limited studies published so far. The first one suggests that digital cities represent the environment salvation of cities in the 21st century. Gay (2002) concludes that E-commerce is more environmentally friendly than the 'bricks-and-mortar' approach to doing business by comparing the energy consumption of E-commerce to that of traditional retailing in five distinctive businesses. The second one claims that digital cities may bring about unintended negative environmental impacts. Galea and Walton (2000) conclude that wider adoption of E-commerce will not lead to greater environmental gains after comparing the traditional and online business models of an American grocery provider. The third argument states that the environmental impacts of digital cities are more likely to be context-based. Marvin (1997) argues that the net environmental impact of the development of telecommunication systems is uncertain because telecommunications will not only reduce travel needs in cities, but will also induce new demands for physical flows and movements. Reichling and Otto (2001) contend

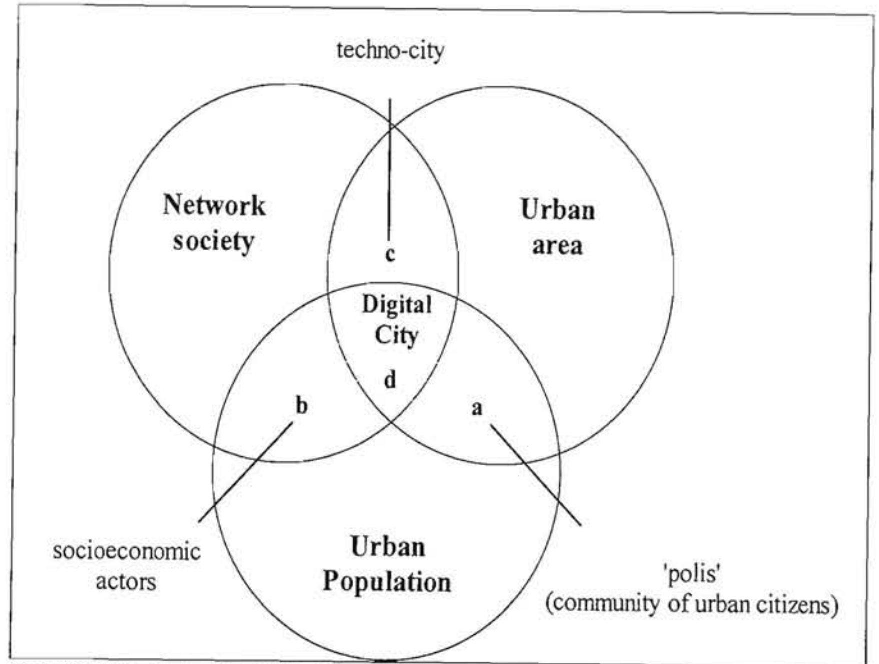

FIGURE 1 Understanding Digital City: The Couclelis Framework
Source: After Coulclelis (2004)

that telecommunication services and new network infrastructure offer new opportunities to increase the efficiency of energy and resource use under certain circumstances, but they are not necessarily more inherently environmentally benign. Zurkirch and Reichart (2001) find that the relative environmental burdens of telecommunication services are determined more likely by the actual context than by how service is provided (e.g. traditional retailing vs. E-commerce). Matthews and his colleagues (2002) explore the energy consumption of online book retailing in the United States and Japan. Their findings indicate that the energy consumption of the book selling business is dependent on multiple factors and the online mode is not necessarily more energy efficient than the traditional mode.

These empirical studies have certainly deepened our understanding of the environmental implications of digital cities, but the evidence obtained so far is not sufficient to paint a complete picture of the environmental consequences of digital cities. The goal of this paper is to fill the gap in the existing literature by conducting a systematic empirical study on the environmental impacts of digital cities. By doing so, we aim to provide more empirical evidence about the regional environmental consequences of digital cities from a macroeconomic perspective. Using the city of Austin as a case study, we address three specific research questions: (1) how has the economic structure of a digital city been transformed? (2)what are the environmental impacts of the emerging digital cities? (3) what are the policy implications for urban environmental management in the digital age?

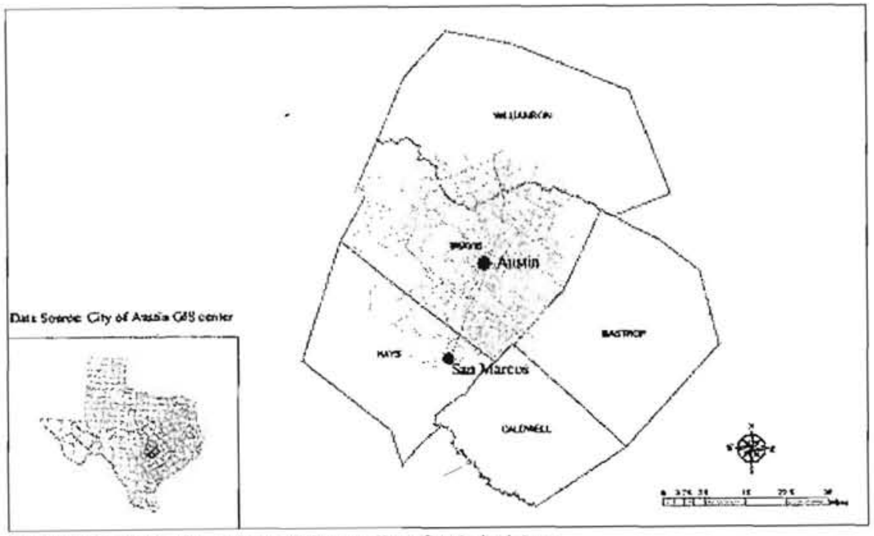

FIGURE 2 Austin-San Marcos Metropolitan Statistical Area
Source: City of Austin, 2003a

The rest of this paper is composed of five sections. First, we provide a brief introduction of Austin's road to Silicon Hills. Then, we present the methods and data sets used in the empirical analysis. Following this, the results dealing with the economic transformation and its environmental consequences for the Austin Metropolitan Statistical Area (MSA) during the 1990s are presented. The following section deals with the environmental impacts of digital cities and Austin's responses to these problems. Finally, we conclude with a discussion on the policy options for the future.

Austin: The Rising Silicon Hills

The city of Austin is located in Travis County, Texas, with scenic hills and pleasant lakes in the west and the Colorado River running through it. The Austin MSA is composed of five counties in central Texas: Bastrop, Caldwell, Hays, Travis and Williamson (Figure 2), which had been sparsely populated until the 1950s. The postwar baby boom and economic takeoff, however, has resulted in the doubling of Austin's population every 20 years on average since 1960. According to the U.S. Census 2000, the Austin MSA had 1,249,763 residents in 2000, and about half of them, 656,562, lived within the city limits of Austin. The Texas Office of the State Demographer (2004) predicted that the population of the Austin MSA would reach 1.9 million by 2020 and that the City of Austin alone would have more than one million residents. In addition, out-of-state immigration accounted for approximately 59 % of the population growth in the 1990s (CAPCO 2003; GACC 2003). The total urbanized area doubled consequently about every 20 years

since 1960 to accommodate the fast growing population (City of Austin 2003b).

Historically, Austinites began to seek their own economic identity right after the city had been chosen to be the state capital in 1872. Yet, this quite Texan city missed three major economic waves that have swept Texas - agriculture, ranching and the more recent one of oil. Austin has never been a favourite city for businessmen and entrepreneurs, but it was always filled with politicians, government employees, educators and students. After World War II, Austin experienced a substantial growth in high-tech industries, especially ICT sectors in a period of a national postwar economic boom. Attracted by cheap land, an adequate high-tech labour force, well-developed infrastructure and pleasant climate, some top-tier high-tech corporations such as IBM, Motorola, and Texas Instruments (TI) began to build assembly branches and research and development (R&D) facilities in the 1960s and 1970s. The fast development of large firms nourished the growth of supporting industries both upstream and downstream in the economic chain. At the same time, UT Austin, the flagship research university in Texas produced many high-tech spin-offs and start-up companies. 1980s was an important decade for Austin in paving its way towards the Silicon Valley of the U.S. South. In 1984, Austin was selected among 57 cities as the headquarters of the Microelectronics and Computer Technology Corporation (MCC), a large private high-tech consortium aimed at the development of new generations of computer. At the same year, Dell was founded with $1000, which would become the top personal computer producer in the United States and the largest private employer of Austin 20 years later. Austin also successfully recruited SEmiconductor Manufacturing TECHnology (SEMATECH) in 1987, a national research consortium that provides R&D opportunities for the study of advanced semiconductor manufacturing techniques and processes. By the late 1980s, the number of high-tech companies in the Austin region had almost tripled compared to that of the late 1970s (Lee 2002) and Austin had emerged as a new rising technopolis in the southern part of the United States. The high-tech 'flowers' that had been carefully nurtured in earlier decades in Austin fully 'bloomed' in the 1990s. By the end of 2000, high-tech sectors accounted for approximately 21 % of total employment in Austin. About three-quarters of the total number of high-tech employees were working in three major sectors: semiconductor and electronics, computer and peripherals, and software and telecommunications, indicating the arrival of a new era for the regional economy (Lee 2002; GACC 2003). The tremendous transformation that occurred in Austin has not gone unnoticed. Austin MSA was ranked number one in the 2004 POLICOM economic strength rankings (POLICOM 2004). This was the fourth consecutive year that Austin MSA led the race among all MSAs in the United States. According to another recent survey, Austin was ranked number three among 150 United States metropolitan areas as one of the best places for business and careers (Forbes 2006). In addition, the unemployment rate in Austin has been continuously dropping during the 1990s, and it remained lower than the state and national averages during the recent nationwide economic depression (USBLS 2003).

Just like any other city and place in the United States, Austin also experienced an economic downturn in the past few years. Symptoms such as a softened labour market, sluggish investment, sliding interest rate, and decreasing consumer spending, were all observed in this city. The economy was obviously battered, yet it has endured. According to an earlier economic forecast, growth in the Austin region would begin to accelerate between 2002 and 2006 if the national economy would recover at the modest rate (City of Austin 2002). Another research report indicated that the Austin economy was slowly but continuously gaining strength since 2002 (Angelou Economics 2004).

In summary, over the past three to four decades, particularly during the 1990s, Austin experienced unprecedented economic growth led by the development of Hi-tech industries, especially ICT-related sectors, resulting in significant gains in population and job opportunities and improvement in major economic indicators such as GDP. Popularly known as "Silicon Hills," defined as a technopolis in the U.S. Sunbelt (Castells and Hall 1994), Austin was recently ranked by Fortune Magazine as one of the 25 most promising cities in the United States. It is also one of the most heavily wired cities with a rapidly increasing number of ICT-related hi-tech companies over the past 10 years. Yet, among the growing academic inquiries about this newly rising digital city (Stewart 1992; Kim 1998; Lee 2002), few have explored Austin from an environmental perspective (Hirsh 1999). This empirical investigation is a modest effort we offer to bridge this gap in the literature.

Methodology and Data

Input-Output Analysis

The methodology of our empirical analysis is based primarily on input-output (IO) analysis and its environmental extension (EIO). The essence of IO analysis is that complicated interactions within an economy can be approximated by proportional relationships among economic sectors. Furthermore, the production level of each commodity is assumed to be determined by the final use of output and the assumed production structure. One noticeable advantage of IO analysis is its flexibility in investigating economic problems at different spatial and temporal scales. The linear nature of IO analysis does limit the scope of its application, but never excludes it from popular applications in studying social, economic, and environmental problems (Miller and Blair 1985).

A standard IO table divides an economy into n purchasing (input) sectors (in rows) and producing (output) sectors (in columns). Thus, the elements of an IO table represent the inter-sectoral flows of an economy over a given period of time. The rows of the table describe the distribution of producers' output throughout an economy, while the columns illustrate the various inputs required by a sector to produce outputs (Miller and Blair 1985). An IO table is composed of four major parts: intermediate industry exchange, final demand, value added, and gross national product. Intermediate industry exchange describes the sales and purchases of goods to (or from) all other sectors. Final demand represents the value of goods and services used by households, government, and exports to other regions. Value added explains employee compensation, profit-type income and capital consumption allowances, and indirect government taxes. The dimension of an IO table varies from just a few to hundreds. The higher the dimension, the more detailed are the economic activities recorded (Figure 3).

<table>
<tr><th rowspan="2"></th><th colspan="4">Producer</th><th colspan="4">Final demand</th></tr>
<tr><th>Sector 1</th><th>Sector 2</th><th>...</th><th>Sector n</th><th>Household consumption</th><th>Governmental consumption</th><th>Investment</th><th>Export</th></tr>
<tr><td>Sector 1</td><td colspan="4" rowspan="4">Intermediate Industry Exchange</td><td colspan="4" rowspan="4">Final Demand</td></tr>
<tr><td>Sector 2</td></tr>
<tr><td>...</td></tr>
<tr><td>Sector n</td></tr>
<tr><td>Employees</td><td colspan="4" rowspan="3">Value Added*</td><td colspan="4" rowspan="3">Gross National Product (GNP)</td></tr>
<tr><td>Owners of business and capital</td></tr>
<tr><td>Government</td></tr>
</table>

FIGURE 3 Four Components of a General Input-Output Model
Source: After Miller and Blair (1985).

The basic IO model can be represented using matrix notation as:

$$X = (I - A)^{-1} Y \tag{1}$$

Where

X = gross output vector
A = technical coefficients matrix
Y = the final demands vector
I = $n \times n$ identity matrix
$(I - A)^{-1}$ = Leontief inverse matrix or the matrix of interdependence coefficients

Equation (1) makes it clear that the output of each sector in an economy is proportional to the level of the final demands of all sectors. While the elements of A matrix explains the compositions of intermediate inputs, the elements of $(I - A)^{-1}$ matrix describe both direct and indirect output change as a response to the change in final demands.

Environmentally Extended Input-Output Analysis

The environmental extension of the basic IO model considers extra intersectoral flows (e.g. natural resources and pollutants) in addition to the traditional economic flows. In this study, an additional direct pollutant emission matrix (*E*) is introduced to extend a standard IO model into an environmental input-output (EIO) model. The basic EIO model can be represented using matrix notation as:

$$P = E(I - A)^{-1} Y$$
$$\text{Let } B = E(I - A)^{-1}, \text{ then } P = BY \quad (2)$$

Where

P	=	total pollutant emission
B	=	total pollutant emission matrix
E	=	direct pollutant (per unit output) emission matrix
$(I - A)^{-1}$	=	Leontief inverse matrix

Equation (2) shows that the total pollutant emissions are proportional to the level of the final demands. While the elements of the *E* matrix (also known as direct pollutant emission coefficients) represent pollutants generated to produce one unit output, the elements of matrix *B* (also known as total pollutant emission coefficients) represent the direct and indirect effect of the per unit change of the final demand on pollutant emission in production.

Following Leontief's seminal work in the 1930s and 1940s (Leontief 1936, 1941), IO analysis was first applied to solve regional and multiregional macro economic problems (Isard 1951; Moore and Petersen 1955; Hirsch 1959; Emerson 1969; Giarratani et al.1976; Polenske 1980; Miernyk 1982; McGregor et al1996; Li and Ikeda 2001; Lenzen et al 2003). It was later extended to the areas of natural resources allocation and pollution abatement issues (Lofting and McGauhey 1963; Cumberland 1966; Leontief 1970; Laurent and Hite 1971; Janicke et.al 1989; Hawdon and Pearson 1995; Lave et al.1995; Matthews 1999; Steenge 1999). The latest expansion of IO analysis is to deal with the social and demographic aspects of input-output economics (Stone 1970; Duchin 1998). Due to space limitation, a more detailed literature review and description of the methodology of IO and EIO analysis are omitted from this paper. Interested readers may refer to the literature cited above.

Structure Decomposition Analysis

Structural decomposition analysis (SDA) is a relatively new methodology that has been adopted since the early 1970s (Leontief and Ford 1971). This analytical tool has made it possible to quantify fundamental 'sources' of change in a wide range of variables, including economic growth, energy use, workforce requirements, trade, and material intensity (Rose and Casler 1996). The primary rationale of SDA is to split an identity into its components. This division can be as simple as

the three-part basic form (technological change, mix, and level), or as complex as desired. Based on the work of Fujimagari (1989) and Sawyer (1992), Wier (1998) uses a six-component model to trace change in the sources of pollutant emissions, the level of final demand, the composition of final demand, IO coefficients, the emission factor, energy intensity, and fuel-mix in the production sectors. A simplified version of Wier's model is adopted and the change in pollutant emissions is considered to come from three components: the level of final demand, the technical coefficient, and the emission intensity factor. The SDA model used in this study can be presented as:

$$E_p^i = [(F_p^i \, M_p \, Q_p)' \, J]' \, (I - A)^{-1} \, Dd \quad (3)$$

Where

i	=	pollutant *i*, such as SO_2, CO, and NO_X, etc.
E_p^i	=	a scalar of total emissions of type *i* from the production sectors
F_p^i	=	a $n \times m$ matrix of emission per unit of total demand for energy for all production sectors
M_p	=	a $m \times n$ matrix of fuel mix in the production sectors
Q_p	=	a $n \times n$ diagonal matrix of energy intensities
J	=	a $n \times 1$ matrix with all elements equal to 1
$(I - A)^{-1}$	=	a $n \times n$ Leontief inverse matrix
D	=	a $n \times k$ matrix of the composition of final demand
d	=	a $k \times 1$ matrix of absolute level of final demand for *k* categories of final demand

Data Sources

Since the ICT sectors in Austin started to take off in the early 1960s and experienced the fastest growth in the1990s, it would have been ideal to extend our empirical analysis from 1960 to 2000. However, due to availability of time series data, especially environmental data, we had to confine our analysis to the 1990s, more specifically, from 1990 to 1999.

Economic Data

The primary data source is based upon 528-sector input-output tables for the years of 1990, 1994 and 1999. IO tables are obtained from Minnesota IMPLAN Group Incorporated (MIG) who compiles IO tables from a wide variety of sources including the U.S. Bureau of Economic Analysis, the U.S. Bureau of Labor, and the U.S. Census Bureau (MIG 2004). IMPLAN version 2.0 pro, the software developed by MIG, is used to build IO models and implement the IO analysis.

7x7 IO models of Austin MSA are constructed on the basis of the original 528x528 IO tables. In other words, the Austin economy is assumed to be com-

TABLE 1 Definitions of the Segments in a Seven-Segment Austin IO Model

Segment	Total sectors	IO table record number	Brief Description
Production	409	All the other items	Agriculture, forestry, and fisheries, mineral industries (excluding sectors from the energy segment), manufacturing (excluding sectors from the ICT segment) etc.
Energy	8	37-39, 213, 443-44, 511-12	Coal mining, natural gas and crude petroleum, electric and gas production and distribution etc.
Information	13	174-76, 178, 181, 371, 441-42, 470, 475, 483-84, 497	Newspapers, periodicals, book publishing, phonograph records, radio and TV broadcasting etc.
Information and Communication Technology (ICT)	17	267, 339-43, 370, 372-78, 400,402, 473	Electronic computers, computer storage devices, computer terminals, radio and television devices etc.
Service	58	446-469, 471-72, 474, 476-81, 485-94, 500-509, 518, 521, 525-27	Wholesale, Food stores, banking, hotel, real estate, hospitals, legal services, social services etc.
Transportation	13	392-93, 433-440, 482, 510, 513	Ship and boat building and repairing, railroads and related services, water, and air transportation etc.
Education and Publication Admin. (Edu_PA)	10	495-96, 498-99, 512, 515, 519-20, 522-23	Federal, state and local government, elementary, secondary schools, colleges and universities etc.

posed of seven economic segments:[2] Production, Energy, Information and Communication Technology (ICT), Transportation, Service, and Education and Public Administration (Edu_PA). Highly aggregated IO models are constructed and analyzed in this study because: 1) highly disaggregated environmental data were not available when this study was conducted; 2) it is still possible, albeit in a much cruder manner, to examine the transformation of the economic structure (the emerging digital economy) and its environmental consequences with seven-segment models, e.g., to compare the assumed growing segments such as ICT, Information, and Service with the assumed declining segments such as Production, Transportation, and Energy. We referred to both the 1987 Standard Industrial Classification (SIC) and 1997 North American Industry Classification Systems (NAICS) to define the segments in this study (Table 1). Output data is deflated using the price deflator provided by IMPLAN.

Environmental Data

Point industrial air emission data, the only available continuous environmental data set, is used as the proxy to explore the environmental impacts of the transformation of economic structure in the Austin MSA. Ten years (1990 - 1999) of air

2. A segment is defined as a collection of economic sectors in this paper.

pollution emission data was extracted from the STARS, an air pollutant database maintained by the Texas Commission on Environmental Quality (TCEQ) that tracks and records all industrial point sources emission of seven air pollutants: non-methane organic compound (NMOC), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter less than ten microns in diametre (PM_{10}), total particulate matter (TSP), and Lead (Pb). Pb is not used in the analysis because emissions from most of the sources are negligible.

The combination of EIO analysis and SDA provides a practical approach from a macroeconomic perspective to explore the environmental consequences of the emerging digital economy of Austin MSA. While the traditional technical coefficient matrices and Leontief inverse matrices explain the trend in the transformation of economic structure, the direct and total pollutant emission matrices illustrate how direct and indirect changes in final demands could impact industrial air pollutant emissions from the manufacturing process. In addition, SDA makes it possible to further investigate the relative contribution of three major sources of pollutant emission: the level of final demand, the technical coefficients, and the intensity of emission factor.

We are fully cognizant that the methodology adopted in this research, just like those in any other previous studies, have limitations, and we would like to bring them to the readers' attention. First, the linearity assumption between sectoral output and pollutant emission would probably not hold in the mostly non-linear real world. The results and conclusions of this study are thus an imperfect representation of what happened in the real world. Second, the highly aggregated IO models are not able to provide insights about the complex economy and environment interactions at a very detailed level. Third, a longer period of the pollution data (e.g. starting from 1980) would have enabled us to examine the issues more thoroughly, however, they were not available when this study was conducted. In addition, this paper presents only the major findings from the seven-segment model; more results and detailed explanation can be found in Tu (2004).

The Transformation of the Economic Structure of Silicon Hills: Results Based on the IO Analysis

Here, we attempt to answer two research questions raised earlier in this paper: 1) what kind of economic structure transformation occurred in the Austin MSA during the 1990s? 2) was there any observable trend (e.g. informatization[3])? The results are organized based on three types of analysis: 1) trends based on the input-output accounts; 2) trends based on the direct effects (technical coefficient matrices) of the input-output models; and 3) trends based on the total effects (Leontief inverse matrix) of the input-output models.

3. "Informatization" refers to the process of development of information activities over time in an economy (Machado 1994).

TABLE 2 Change of Intermediate Output, Final Demand, and Total Output in the Segments of the Austin Economy, 1990 - 1999[4]

	Intermediate output	Final demand	Total output
Production	173%	121%	156%
Energy	-5%	-25%	-15%
ICT	313%	408%	340%
Information	299%	251%	298%
Transportation	98%	87%	93%
Service	171%	208%	179%
Edu_PA	145%	35%	139%

TABLE 3 Segment Shares in Total Output, 1990 - 1999

	1990	1994	1999	Change (1990 - 1999)
Production	18%	17%	16%	-8%
Energy	7%	3%	2%	-69%
ICT	6%	8%	10%	58%
Information	11%	15%	16%	43%
Transportation	3%	3%	2%	-31%
Service	45%	45%	45%	0%
Edu_PA	10%	9%	9%	-14%

Trends Based on Input-output Account

Table 2 shows that six out of seven segments of the Austin economy experienced significant growth in intermediate output, final demand, and gross output in the 1990s. The ICT and Information segments apparently grew much fast than other segments on all three measurements. The Energy segment was exceptional as it had negative growth according to all three measurements.

Table 3 demonstrates the change in the segment shares in total gross output. The ICT, Information, and Service segments expanded, while the Production, Energy, Transportation, and Edu_PA segments diminished during the 1990s. Table 4 indicates that in order to produce one unit of output, fewer inputs were required from the Production, Energy, Transportation, and Edu_PA segments but at the same time, more inputs were required from the ICT, Information, and Service segments.

Regarding the structure of final demand, the shares of the ICT and Information segments increased approximately 45 % and 40 % respectively, while the share of Energy segment decreased by nearly 67 %; the shares of the Transportation, Edu_PA, Service, and Production segments also decreased, although at much lower rates (Table 5).

4. All data in this table and after are original except when indicated otherwise

TABLE 4 Segment Shares in Intermediate Output, 1990 – 1999

	1990	1994	1999	Change (1990 - 1999)
Production	25%	24%	21%	-14%
Energy	15%	5%	4%	-71%
ICT	8%	10%	16%	97%
Information	1%	1%	1%	36%
Transportation	6%	8%	4%	-27%
Service	44%	50%	52%	20%
Edu_PA	2%	1%	1%	-48%

TABLE 5 Segment Shares in Final Demand, 1990 – 1999

	1990	1994	1999	Change (1990-1999)
Production	16%	15%	15%	-4%
Energy	5%	3%	2%	-67%
ICT	6%	7%	8%	45%
Information	14%	19%	20%	40%
Transportation	2%	1%	1%	-31%
Service	45%	44%	43%	-5%
Edu_PA	13%	11%	11%	-14%

Trends Based on Direct Effect

Table 6 presents changes in the elements of the A matrix (technical coefficients) -- the value of inputs purchased from all sectors in the economy per dollar of output for a particular sector. The direct input from the Energy, Transportation, and Edu_PA segments decreased in all segments, indicating fewer inputs were purchased from these segments to produce per dollar of output in all segments. The direct input from the Production segment decreased in all but the Energy segment. The required inputs from the Information, ICT, and Service segments to produce per dollar of output for all the segments increased except for the purchase of the ICT segment from the Production segment. The above results indicate that the Austin Economy was less dependent on the Production, Energy, Transportation,

TABLE 6 Change in the Shares of Column Sum of A Matrix, 1990 – 1999

	Production	Energy	Information	ICT	Transport.	Service	Edu_PA
Production	-3%	67%	-40%	-41%	-10%	-22%	20%
Energy	-58%	-24%	-74%	-65%	-77%	-63%	-80%
Information	90%	218%	53%	103%	85%	50%	141%
ICT	-4%	77%	91%	24%	8%	36%	46%
Transportation	-11%	-7%	-58%	-23%	-26%	-33%	-25%
Service	34%	57%	-4%	32%	38%	5%	16%
Edu_PA	-36%	-40%	-61%	-58%	-27%	-52%	39%

TABLE 7 Change in the Shares of Leontief Inverse in the Total Output Multipliers, 1990 – 1999

	Production	Energy	Information	ICT	Transport.	Service	Edu_PA
Production	0%	26%	-20%	-49%	-5%	-25%	-59%
Energy	-62%	-10%	-69%	-75%	-74%	-69%	-93%
Information	98%	142%	6%	71%	108%	52%	-15%
ICT	-1%	39%	125%	0%	19%	27%	-49%
Transportation	-14%	-26%	-43%	-40%	-2%	-37%	-74%
Service	33%	27%	26%	6%	45%	0%	-58%
Edu_PA	-38%	-51%	-48%	-64%	-26%	-54%	0%

and Edu_PA segments, but more dependent on the Information, ICT, and Service segments.

Trends Based on Total Effect

Table 7 compares the segmental inputs for 1990 and 1999 required to satisfy the per dollar increase in final demand for each of the seven segments. The results indicate that: 1) input requirements from the Information, ICT, and Service segments increased in general; and 2) input requirements from the Production, Energy, Transportation, and Edu_PA segments decreased in general[5]. The results from the analysis of the change of elements in the total flow matrix[6] (Table 8) again confirm the findings of the previous measurements, i.e., the Austin economy was more dependent on the Information, ICT, and Service segments, while less

5. The Edu_PA segment was an exception because the inputs of this segment were mainly from non-production factors (e.g. wages). There were also a few other exceptions that were not consistent with the general conclusions.
6. Total flow multiplier is the ratio of change in total output of segment j to change of total output of segment i caused by the change in final demand.

TABLE 8 Changes of Elements in the Total Flow Matrix, 1990 – 1999

	Production	Energy	Information	ICT	Transport.	Service	Edu_PA
Production	0%	40%	-25%	-49%	-3%	-13%	-59%
Energy	-62%	0%	-71%	-75%	-73%	-69%	-93%
Information	99%	168%	0%	71%	112%	51%	-15%
ICT	0%	54%	112%	0%	21%	27%	-49%
Transportation	-14%	-18%	-46%	-40%	0%	-37%	-74%
Service	33%	41%	19%	6%	48%	0%	-58%
Edu_PA	-38%	-46%	-51%	-64%	-25%	-54%	0%

dependent on the Production, Energy, Transportation, and Edu_PA segments at the end of the 1990s.

Environmental Implications of the Emerging Digital City

Far away from tall smokestacks and effluent pipelines, Austinites have long been used to clean water, green hills, and clear skies. The only major natural environmental threat -- flooding -- has long become history after the completion of a network of dams and lakes northwest of the city in the early 1960s. Human history has, however, proved that environmental problems are always closely associated with the level and stage of economic development (Grüber 1998). So, what are the environmental consequences of the tremendous structural transformation in the Austin economy during the 1990s? Has Austin become more environmentally friendly? What are the major environmental problems that are challenging Austin as it becomes more digital? What has been done to deal with the emerging environmental problems? We attempt to shed some light on these questions below. First, we illustrate the major findings from EIO and SDA based on the IO tables of 1990, 1994, and 1999; second, we document the main environmental management approaches of Austin since the mid-1980s; third, we summarize the major environmental challenges of Austin and their policy implications in the information age.

Major Findings from EIO and SDA

EIO is used to quantify both the direct and indirect impacts of changing economic structure on point industrial air pollutant emissions in Austin during the 1990s, while SDA is adopted to quantify the contribution of three fundamental "sources" (final demand, the technical coefficients, and the intensity of emission factor) that impact pollutant emissions. Both direct and total pollutant coefficients are calculated and SDA is implemented for six pollutants. The direct pollutant coefficients explain pollutant emissions directly related to sectoral production, while the total

TABLE 9 Change in Direct Pollutant Coefficients, 1990-1999

	1990-1994		1994-1999		1990-1999	
	Production	Energy	Production	Energy	Production	Energy
TSP	-21%	81%	-52%	150%	-62%	352%
PM_{10}	-53%	1072%	0%	614%	-53%	8267%
SO_2	-76%	-22%	191%	-33%	-31%	-48%
NO_x	-31%	66%	-34%	-1%	-54%	65%
NMOC	N/A	34%	-85%	41%	N/A	89%
CO	1469%	90%	-58%	27%	565%	142%

TABLE 10 Change in Total Pollutant Coefficients for Selected Pollutants, 1990-1999

	Production	Energy	Information	ICT	Transport.	Service	Edu_PA
TSP	-61%	230%	-65%	-33%	-64%	-82%	-82%
PM_{10}	-51%	1789%	-53%	-69%	-50%	-73%	-73%
SO_2	-41%	-53%	-64%	-75%	-68%	-91%	-91%
NO_x	-50%	48%	-55%	-61%	-52%	-87%	-87%
NMOC	101%	69%	-65%	183%	-54%	-93%	-85%
CO	256%	120%	64%	39%	45%	91%	-69%

pollutant coefficients capture both direct and indirect pollutant emissions.

Direct Pollutant Emission Coefficients

The emissions of point industrial air pollutant were concentrated in two segments, Production and Energy. For the Production segment, the TSP, PM_{10}, SO_2 and NO_x coefficients decreased; the CO coefficient increased, and the NMOC coefficient could not be calculated because the raw emission data were incomplete. For the Energy segment, the TSP, PM_{10}, CO, NMOC and NO_x coefficients increased; and the SO_2coefficient decreased (Table 9).

Total Pollutant Emission Coefficients

For the Production and ICT segments, the coefficients TSP, PM_{10}, NO_x SO_2 decreased, and the NMOC and CO coefficients increased. For the Information, Transportation and Service segments, the TSP, PM_{10}, NO_x SO_2 CO and NMOC coefficients decreased compared to the increase in the coefficient for CO. The coefficients of all the pollutants decreased in the Edu_PA segment. For the Energy segment, the TSP, PM_{10}, CO, NMOCand NO_x coefficients all increased, and only

TABLE 11 Sources Change of Pollutant Emissions for Selected Pollutants, 1990-1999

	Technical Coefficient	Emission Intensity	Final Demand	Export	Sum
TSP	-192	-792	1198	28	242
PM_{10}	-99	-354	712	74	333
SO_2	-1086	-1038	2103	-55	-75
NO_x	-2836	-339	4972	568	2365
NMOC	-82	-301	446	186	95
CO	-439	1868	482	171	307

Note: 1. Unit = ton.

the SO_2 coefficient decreased (Table 10).

For both direct and total pollutant coefficients, more cases are observed to decrease than to increase except for the Energy segment during the 1990s. Based on the results of analysis, the air pollutant emissions in terms of per unit output generally decreased in the manufacturing process of the Austin economy during the 1990s. On the other hand, further investigation is necessary to collect more evidence and to explain the reverse trend that occurred in the Energy segment.

SDA Results

As explained in the methodology section, the total change in emissions of pollutants from time (*t*-1) to time (*t*) can be explained using three variables: 1) the emission intensity; 2) the technical coefficient; and 3) final demand. The former two factors are closely related to manufacturing process, and the latter is associated with the consumption side of economy. The results from our analysis indicate that the environmental gains obtained from the adjustment of economic structure (change in technical coefficients) and decreasing emission intensity have largely been offset by increase in the level of final demands (Table 11). While the manufacturing process has been responsible for less point industrial air pollution, the contribution of pollution from the consumption side (final demand) has been increasing at the same time.

Environmental Challenges of the Rising Silicon Hills

As a college town and state capital, Austin has never experienced severe pollution and immediate environmental emergency as many other cities have in the past decades. The preliminary results from EIO and SDA suggest that the manufacturing process of the Austin economy generally produced less air pollutants in the 1990s. The fact is that the total economic output of Austin increased much faster than the total pollutant emissions except for CO during the 1990s (Table 12). The

TABLE 12 Annual Industrial Point Air Pollutant Emissions at Austin MSA, 1990 – 1999

	TSP	PM_{10}	SO_2	NO_X	NMOC	CO
1990	985.66	565.64	2746.66	6858.72	405.64	887.5
1992	872.73	495.89	2594.23	6908.89	744.14	1304.77
1993	1080.3	516.24	3111.9	7214.91	700.34	3210.61
1994	1174.83	407.8	1349.65	8058.71	914.16	3759.87
1995	1233.88	470.13	1754.2	8773.51	481.78	3594.51
1996	1213.27	448.77	1646.84	8731.62	644.61	3791.37
1997	1011.01	487.64	1875.25	8110.62	444.94	3587.94
1998	1181.2	905.26	1521.14	9006.63	570.68	5183.68
1999	1228.03	898.64	2671.42	9223.05	546.97	3653.5
Change rate (1990-99)	24.59%	58.87%	-2.74%	34.47%	34.84%	311.66%

Note: 1. There is no record available in 1991.

annual reports released by the Central Texas Sustainable Indicator project also showed that the environmental condition in Austin had been stable, if it has not been significantly improved in recent years (CTSIP 2004). So, will Austin be free of significant environmental challenges in the emerging information age? Our answer is negative because environmental problems have always been, and will always be evolving with major technological innovations and subsequent changes in economic systems. As an emerging digital city, Austin is facing at least three major environmental challenges:

1. Challenges Related to the Growth

Since the early 1980s, Austin has been challenged by increasing environmental problems brought on by the unprecedented population and economic growth and the corresponding rampant urban sprawl. The collapse of overloaded wastewater systems in the mid-1980s, for example, has led to millions of gallons of inadequately treated sewage being discharged into Barton Creek and the Colorado River. The sewage had to be ferried from the area served by overburdened treatment plants to other areas with surplus treatment capacity - this was later labeled "Sewage on wheels" (Northcott 1987). Not surprisingly, traffic conditions in Austin also started to deteriorate from the 1980s onwards accompanied by rising congestion-related costs. "Pray for me - I drive 183", read a popular bumper sticker in the late 1980s that expressed the concerns about the worsening traffic conditions at Austin on the part of a worried general public (Renfro 1990).

The unparallel economic growth in the 1990s pushed the urbanization of Austin to an unprecedented level. In 1999, 75 % of new houses were built outside the city limits (Briseno 1999). Between 1997 and 2000, approximately 30 % of the building permits issued by the City of Austin were within the Austin Drinking Water Protection Zone (DWPZ), a groundwater aquifer beneath the western one-third of Austin that is ecologically unsuitable for intensive development (Sui et al.2004). The liberal annexation law of Texas also helped accelerate the suburbanization process in Austin. Continuously rising land prices inevitably led to high density development that may further jeopardize the water quality and scenic beauty of Austin, especially in the more environmentally sensitive northwest part. One survey conducted in the early 1990s revealed that a high percentage of the general public complained about the degradation of environmental quality despite the booming economy (Beatly and Brower 1994). A more recent study, The Central Texas Sustainability Indicators 2004 (CTSIP 2004), reported that approximately 75 % of residents did not believe that the natural environment of Austin had been improved.

2. Challenges Related to the Service and ICT Segments

The environmental consequences related to these two segments, although much less studied, may become the major environmental challenges for Austin in the information age. The pollution from the Service segment is problematic due to both the magnitude and the unique nature of the pollution sources in the Service segment. In the 1990s, the Service segment accounted for more than 45 % of Austin's total output, and the ICT segment grew the fastest among the seven segments. Pollution sources of the Service segment are usually small in scale, large in quantity, widely distributed, individually negligible, collectively harmful, and difficult to identify and regulate (Esty and Chertow 1997). The ICT segment, on the other hand, has two levels of negative environmental impacts: direct impacts related to ICT products such as the long-term toxicity and environmental impacts of the chemicals released through the entire life-cycle of ICT products and indirect (high-order) impacts related to the application of ICT such as the problems related to energy consumption and rebound effects (Langrock et al 2002).

3. Challenges Related to the Nature of Digital Cities

Theoretically, digital cities are different from traditional cities in that the creation, transformation, and dissemination of information are replacing material production and transformation to become the major activities of the regional economy. The interaction and substitutability between information and energy/material flows may greatly impact the environment of the physical world (Spreng 1993; Chen 1994; Sui and Rejeski 2002). Although the substitution effects have yet to be empirically studied, their environmental implications for digital cities are profound and worth further investigation.

Austin's Responses to the Emerging Environmental Problems

In the past two decades, the City of Austin has dealt with environmental problems mainly through governmental regulations, city ordinances, urban planning, and individual environmental initiatives and programs. While these measurements have effectively mitigated much growth-related environmental nuisance, they will be generally much less useful in treating the emerging environmental problems that are challenging digital cities.

Governmental Regulations

In Austin, environmental problems are managed by separate divisions under city council according to the nature of the problems, such as air pollution, water contamination, and solid waste generation. The primary responsibilities of these divisions include: 1) the development and implementation of programs to alleviate negative environmental impacts of business and activities in the region; and 2) the promotion of environmental-related education in local businesses and communities. The City of Austin also actively cooperates with environmental and natural resource management agencies and non-government organizations (NGOs) at regional, state, and federal levels, such as the Capital Area Planning Council (CAPCO), the Greater Austin-San Antonio Corridor Council (GAACC), the Texas Commission on Environmental Quality (TCEQ), EPA Region 6, and the Clean Air Force of Central Texas.

Ordinances and Planning

Ordinances and urban planning are treated as major policy instruments to regulate development and lessen negative environmental impacts. Some significant examples include Austinplan, the Northwest Area Land Use Guidance Plan and the Comprehensive Watersheds Ordinance (Kim 1998). The grass-roots Save Our Spring (SOS) movement also played a significant role in protecting the Edwards Aquifer from development-related pollution in the 1990s.

In 1980, Austin city council proposed Austin Tomorrow, an urban planning program aiming at protecting the natural environment by minimizing the negative impacts of economic growth. Thousands of citizens have been actively involved in the development of the plan. In 1985, Austin voters approved an amendment to make Austin Tomorrow (with a new name "Austinplan") a mandatory guideline to direct urban development along a healthier path. However, due to strong resistance from the development communities, the lack of fiscal support, and the inadequacy of administrative incentives, the preferred growth corridors outlined in the plan were not be strictly followed in subsequent urban development.

In December 1984, the planning department of the City of Austin released the Northwest Area Land Use Guidance Plan (NALUG) to direct the development at about 77 square miles of land in northwest Austin. Although NALUG was a compromise solution among various stakeholders without legal binding power, it has played a critical role in balancing development and environmental protection in the area.

In May 1986, the city council passed the first environment-related ordinance, the Comprehensive Watersheds Ordinance (CWO), after intensive debates between pro-development and pro-environment groups. CWO was designed to control non-point source pollution by designating environmental standards for development within the watershed of the Austin region. CWO also proved to be a happy ending for both sides: land developers won a bit more time to adjust their development plans; environmentalists were happy about the requirements of density and buffer zone control in new land development plans.

At the beginning of the 1990s, the enormous development plans proposed by some business giants made a group of Austinites believe that the existing CWO would not be sufficient to protect Barton Creek and Barton Springs from development-related pollution. A grass-roots environmental organization, Save Our Springs Coalition (SOSC), was founded in 1991. SOSC drafted and proposed a new "The Save Our Springs Ordinance" to the City Council. The major provisions of the ordinance include the requirements of setting maximum limits of impervious cover and a stream buffer zone control for all new development. In spite of strong opposition from the major developers, the ordinance was approved marginally by Austin voters in August, 1992. Subsequently, SOSC (later renamed the SOS Alliance, SOSA) had to defend (successfully) the ordinance in the courts. Recently, the SOSA is working with other citizen groups to expand the protection to the Greater Edwards Aquifer Ecosystem (Hirsh 1999; SOS Alliance 2004).

Individual Initiatives and Programs

With increasing environmental consciousness and acceptance of the concept of sustainable development, the urban managers of Austin and the community as a whole finally realized that the traditional "piecemeal" approach to environmental management would be unable to ensure the city's long-range sustainability, and a more holistic management approach was greatly needed to integrate the economic, environmental and social aspects of future development. In the middle of the 1990s, the City of Austin's Sustainable Communities Initiative, UT Austin, and some community leaders began to develop a sustainable indicators system to help the community gauge the successes and challenges of regional development. In 1999, the Central Texas Sustainable Indicator Project (CTSIP) was kicked off by a regional survey -- "Thumbs Up! For the Economy, the Environment, and the Community" (CTSIP 2004).

The first annual report of the project was released in March 2000, covering three of the five counties of the Austin MSA, Travis, Hayes, and Williamson. The latest CTSIP 2004 report extended to cover the two other counties of Austin MSA -- Bastrop and Caldwell (CTSIP 2004). CTSIP comprehensively examines facts and trends in regional development using forty indicators and provides both decision makers and the general public with a relatively complete picture about the three perspectives of sustainable development: economic development, environmental protection, and social equity. While the annual reports of the CTSIP supply abundant amounts of anecdotal information, they seem to be more descriptive than analytic, focusing more on the direct and short term than indirect, long-term environmental threats that may be more significant to a digital city in the information age.

In early 1998, the City Council of Austin launched Smart Growth Initiative (SGI), a long-range urban development plan to guide and shape future urban growth to minimize the negative environmental, economic, and social impacts and to preserve the best aspects of life in the region. There are three major goals of the initiative: first, to determine where and how to grow; second, to improve the quality of life; and third, to enhance the tax base (City of Austin 2003c). According to a preliminary study (Sui et al 2004), SGI does not appear to have worked very well in the first few years of implementation. The expected outcomes of the SGI, to increase construction in encouraged development zones and to reduce construction in protected development zones, have not been observed. As a recent effort to balance fiscal equity, promote environment sustainability, and integrate community, whether SGI will be able to prevent Austin from Houstonizing has yet to be demonstrated.

Summary and Conclusions

Contrary to many previous Utopian predictions, the emerging digital cities have neither pronounced the death of distance nor spelled out the end of geography in the information age (Graham 2000). Instead, cities and regions in the global economy have become more important than ever (Storper 1998; Sassen 2002). The goal of this paper is to make a modest attempt to examine empirically the environmental implications of a city that is being transformed into a digital one. Our empirical results show that Austin has rapidly risen from a quiet college town and state capital to be a prosperous and dynamic digital city as the country is marching into the digital economy and information society into the 21st century. As revealed from the results of the empirical studies, it is clear that: 1) information activities have grown considerably during the 1990s in the Austin economy; 2) the economic segments became more dependent on inputs from the Information, ICT and Service segments; 3) the economic segments became less dependent on inputs from the Production, Energy, Transportation and Edu_PA segments; and 4) while the Production segment was generally generating less air pollution, the pollution from the ICT, Information and Service segments, and the demand side of the economy (final demand) have become more significant to the economy.

There is little doubt that Austin will continue its current growth trajectory in the foreseeable future. While we applaud the economic achievements of Austin,

more attention must be paid to the emerging environmental challenges accompanied by the rapid economic transformation in this digital city. We believe that Austin has a great deal to learn from Silicon Valley, which is widely known as the largest production base of ICT-related products of the world. However, this hi-tech paradise has taken its toll on the environment. Santa Clara County, the centre of Silicon Valley, has 29 EPA Superfund sites, more than any other county in the United States in addition to 150 polluted groundwater sites (SVTC 2004). In the case of Silicon Hills, the potentially negative environmental impacts, particularly related to the ICT industries and service sectors have neither been fully understood, nor have they been sufficiently addressed by policymakers and urban managers. It will be indeed very unfortunate for Austin to repeat the mistakes of Silicon Valley.

In summary, entering into a new promising stage of economic development, Austin, the rising digital city, is also facing new environmental challenges. Our key message to policymakers and urban managers are as follows: 1) the digital economy, centering in ICT sectors, has emerged and will continue to prosper in the Austin area; 2) the quantity, source and structure of environmental threats are evolving with the transformation of economic structure in digital cities; 3) the net environmental impacts of the new type of city is far from clear; and 4) a parallel reform of urban environmental management is necessary to maintain an 'evergreen' Silicon Hills in the information age.

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