CAST – CITY ANALYSIS SIMULATION TOOL: AN INTEGRATED MODEL OF LAND USE, POPULATION, TRANSPORT, AND ECONOMICS

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Abstract: The paper reports on research into city modelling based on principles of Science of Complexity. It focuses on integration of major processes in cities, such as economics, land use, transport and population movement. This is achieved using an extended Cellular Automata model, which allows cells to form networks, and operate on individual financial budgets. There are 22 cell types with individual processes in them. The formation of networks is based on supply and demand mechanisms for products, skills, accommodation, and services. Demand for transport is obtained as an emergent property of the system resulting from the network connectivity and relevant economic mechanisms. Population movement is a consequence of mechanisms in the housing and skill markets. Income and expenditure of cells are self-regulated through market mechanisms and changing patterns of land use are a consequence of collective interaction of all mechanisms in the model, which are integrated through emergence.

Keywords: city modelling, complexity, emergence, land use, integration

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1 INTRODUCTION

Humans almost from the start have used abstraction and simplification to try to understand and then influence the complex processes around them. Modelling is one well-established approach to trying to gain understanding in order to influence.

As cities are a major focus of human activity and complex, humans have long tried to understand and influence their form and processes. In doing so they have developed theories of development and models of change to aid understanding. The concepts underlying the theories and models often reflect the more widespread outlook of philosophy and science prevalent in society at that time. There is a dialogue between urban theorists and modellers and urban planners and builders.

With the rise of the modern science the model of clockworks, based on Newtonian physics, was widespread. This however was often based on a linear and reductionist outlook. Cities, being multi-layered, heterogeneous, extremely complex and going through constant change without any equilibrium, were and are difficult to understand on this approach. Cities are clearly very much greater than the sum of the parts. A myriad of individual actions combine together to make large patterns, such as movements of people, information, goods and money. These flows in turn influence the physical shape of the city. All these processes, and more, are interconnected and cascade across the city from one location or field of activity to the entire city (Batty & Torrens, 2001). In addition cities are contested places, with conflicting interests and desires for use based on class, gender, race, economic interests, aesthetics and so on.

City planning developed significantly at the end of the 19th century and into the 20th century. This was driven by the explosive growth of cities and population due to the industrial revolution and concerns about mass poverty, widespread disease and ill-health and in some case fear of revolution. Great plans were drawn up to re-shape cities. Some concentred on adding to the beauty and monumental nature of cities with grand boulevards, vistas and significant buildings. Others were driven by the aims of removing slums and creating open spaces and parks. Underlying many was the simple idea that if the physical form of the city was changed the social conflicts would diminish, poverty and disease would be reduced, and the economic life of the city would improve. Many of these were based on simple linear models and concepts about cities. In addition the rise of the motor car added another motive (and re-enforced a linear approach) for re-designing cities – the need to speed cars traffic through the city. (Hall, 1988)

Beginning around the 1960s there was a growing reaction to the urban plans based on linear models. Authors such as Alexander (1965), Jacobs (1965) and McHarg (1969) pointed to the rich multi-connections, the organic nature of cities and their complexity. This growing understanding of the complexity of cities was part of wider appreciation, in part fed by the growth of biological and evolutionary science, that reality was complex and therefore linear and reductionist science was of limited value. This trend grew to produce the ideas of Complexity Science.

Another major influence on urban modelling in the last 40 years has been the development of the computer. Before the development of computers, developing models was time consuming and were mainly conceptual outlooks, drawings and plans and physical models. As the data handling power of computers grew it became possible to model many factors and layers, geographically map data (GIS) and to attempt to capture the diversity of cities in models.

However until recently, even most computer models, although handling large amounts of data and multiple options with outputs enhanced by fancy graphics, have based their modelling on linear approaches (Batty & Torrens, 2001). In the last decade there have been various moves to use ideas from Complexity Science to explore and model cities and their changes.

Concerns with sustainabily, global economic competitiveness, regeneration, urban sprawl and social inclusion have all encouraged recent attempts to model cities. However given the complex and complicated nature of cities and the issues, this is no easy feat.

Models are often judged by their predicative powers. However this assumption is not suitable for city models. As cities have an enormously rich complexity both within themselves and in their relations with the wider world, it is impossible to make accurate predictions into the future. In addition as cities are contested places, there cannot be one right or wrong answer to long term urban planning. Models are, and should be viewed as, aids to decision making which remains a political process.

Some urban models are very much tied to one city or consider one facet of the urban scene, such as air pollution or transport.

Analysis of state of the art carried out by the research team has identified that the main differences between CAST and other models are in the higher integration of mechanisms of operation of the city and in the higher level of detail of processes in cells. As CAST is being developed in collaboration with prospective end users it is believed that it addresses some of the key issues required by decision makers.

CAST, based on complexity, is a non-predicative tool which gives a range of future scenarios of possibilities in 10 or 15 years exploring different options of what urban development and change may look like. Due to its integrated nature, it is believed that the end result of this work would be a “city processor”, capable of modelling cities and exploring the space of development possibilities. The paper will report on theoretical basis for the model, and on field trials conducted with GIS data from several European municipalities.

2 STATE OF THE ART

In this section we review the state of the art of city modelling, which we divide into five broad categories: theoretical models; geometry based models; process based models; agent based models; and rule based models. Each of these categories are discussed in more detail in the text below.

2.1 Theoretical Models

Theoretical models approach city modelling from the point of view of mathematics and physics, and attempt to make general theories about processes in cities. These models are very theoretical, and rely on considerable knowledge of mathematics and physics. They can often explain processes in just one city, and only during a certain period of time. They are far removed from providing useful information to planners and decision makers.

Schweitzer has done work using the concepts of Brownian motion to develop theoretical models of self organisation within urban and human processes (Schweitzer & Holyst, 2000; Schweitzer & Tilch, 2002; Schweitzer, 2002 & 2003). One of the key ideas is the self-assembly of network-like structures between a set of nodes without using pre-existing positional information or long-range attraction of the nodes. The model is based on Brownian agents that are capable of producing different local information and respond to it in a non-linear manner.

Others who have explored cities through these theoretical models include Haag (1989).

2.2 Geometry Based Models

Geometry based models are not concerned with processes, but only with application of fractal patterns to city modelling. As these models do not consider micro processes in cities, they have a limited use for decision making. Various authors have worked on such models such as Frankhauser (1994).

2.3 Process Based Models

Process based models are developed from the ideas of Complexity Science based on Cellular Automata. The core idea is that rules operate at the cell level so that the character of the city and its processes emerge for the actions in and interactions between cells. There has been significant work exploring the potential of this approach and it has been useful to examine the broad process of urban sprawl. While these models can be useful for decision makers, their usefulness is limited because of the simplification of the processes. Generally these models lack economic rules and in some cases the cells can only connect with their immediate neighbours as in traditional Cellular Automata (CA) models, unlike areas in real cities.

Batty and co-workers created DUEM (Dynamic Urban Evolutionary Modeling) (Batty & Xie, 1994; Batty, Xie & Sun, 1999) and developed this into IDUEM (Xie & Batty, 2003). These and the SLEUTH model (Clarke, Hoppen, & Gaydos, 1996; Clarke, Hoppen & Gaydos, 1997; Silva & Clarke, 2002) concentrate on the processes and patterns of urban growth. These do not examine people's movements or economic processes within the city. Other CA based models include Simland (Wu, 1996) and the work by White et al. (1997 a & b).

2.4 Mobile Agent Based Models

Mobile agent models, while also based on Complexity Science, rather than focus on cells, as in process models, are based on the emergent properties of the actions of mobile agents that move through the city, which represent major players in a city's development. Usually the actions of agents, people, businesses, etc, are aggregated to simplify the calculations. These models, again have their uses, but are limited in their ability to deal with land use changes.

Examples of agent based models are contained in the work of Semboloni's CityDev (2003), Portugali (1999), including CogCity (Cognitive City) and Benenson (1998) and Torrens (2003), including SprawlSim (2002).

2.5 Rule Based Models

Rule based models are widely used to analyse specific issues, such as transport or air pollution as well as modelling of cities. They are based on largely linear rules which are generalisations of past experience, so that if a certain condition happens it has defined results. Usually the rules are applied in a top-down way at a citywide level, taking an aggregate view of the city. These models are able to handle large amounts of data and many fields of study such as population, economic activity and employment, land use and transport. They can deal with diverse choices of priorities, producing scenarios covering many impacts. These models indicate the range of possible impacts. Also, depending on the rules, they can cover issues environmental impacts of economic decisions. They can be tailored to deal with a specific city.

A number of these models have been developed for analysing cities, including CUF (California Urban Futures model) looking at changing land use (Landis & Zhang, 1998); 'What If?' a programme that links with GIS to examine urban change scenarios, especially in cities experiencing rapid growth (Klosterman R, 1999) and UrbanSim looking at land use and transport use and their environmental impacts (Waddell & Evans, 2002). Clearly there are differences between these modelling methods and exactly what issues are focused on.

One recent and useful example is QUEST (http://www.basinfutures.net/play_gb_quest.cfm), developed by the Sustainable Development Research Initiative in Vancouver to explore sustainable futures for the Georgia Basin area of South Western British Columbia. QUEST is an interactive computer model, with highly visual and user friendly software, that allows people to develop "what if?" scenarios for the future of the region. Its purpose is to aid the public and policy makers explore options for a sustainable future. It handles a large amount of data about the region and works through deterministic formulae based on best knowledge.

The downside of rule based models is that, as they are based on a top-down approach, they fail to represent the complexity of cities, the variations within a city and the dynamic nature of change.

2.6 Summary of the state of the art

Rule based models have a longish history in city modelling and while providing useful support for planners, policy makers and public are limited as they are not based on the complexity of cities. The models based more on Complexity Science, include a growing are of work, but up until now have largely either been developed to explore the theoretical relationship between cites and complexity or to examine broad issue such as urban sprawl. As such they greatly simplify the processes within cities and do not integrate key processes including economics, land use, and transport (Batty & Torrens, 2001). Also a number of these models have not been designed in collaboration with prospective users, and therefore it is questionable how they address the end user needs.

In the next section we look into methods used by CAST, which attempts to overcome some of disadvantages of existing city models.

3 CAST METHOD

3.1 Cells and Processes

Cities and regions are open self-organising systems that have operated for hundreds and even thousands of years. As explained earlier cities are complex with their many-layered physical networks of communication and service routes and human, economic and social relations. Many of these networks and the choices that people make are not controlled by any central government, economic or business power, policy or rules, but rather are based on the individuals' own decisions. The visible and physical form of cities is their built environment but underlying the city, driving all its activities, are human actions.

One way to consider the actions and change of cities is draw analogies from biology. A city is made up of cells, areas of use defined by different functions just as an organism has different cell types such as bone, muscle and internal organs. Cities also have communication networks of roads railways etc just as organisms have blood circulation and nervous systems. Through these cells flow materials, energy and information and within the cells matter, energy and information is stored and transformed (Fig. 1).

CAST uses the ideas of Complexity and develops upon Cellular Automata approaches with the aim of capturing the key processes with in cities. Cellular Automata models usually confine interaction between cells only to the cells immediately adjacent to the cell which is the being considered. Clearly in a city the interactions between cells is much more extended. In theory any cell in the city can have an impact on any other cell. CAST recognises the extended networks of cell connections while also understanding that the connections are not equal as proximity, road networks etc create an uneven geography of connections.

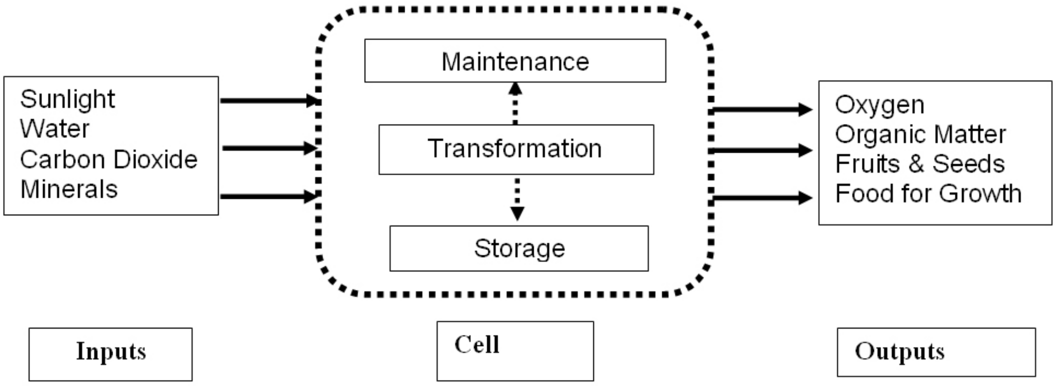


Figure 1 Processes in a biological cell

The structure of CAST is based upon cells that represent the build environment, the land use type, in other words the function of the cell. Unlike the natural world, structures (and non-build space) in the human environment are a product of human purposes. In addition flowing through the cells, driving their changes, are humans and their actions, their metabolism.

Rather than aim to capture the activity of each individual in a city, possibly millions, CAST summarises the activities of the population of a cell. This simplifies the number of calculations and recognises that it is impossible to capture the choices and actions of individual people, but statistics can reasonably accurately describe the actions of groups of people.

CAST uses a Raster based grid which divides the city into cells, usually of 1 hectare (100 metres by 100 metres). The classification of the cell type is based on the majority land use type. Fine detail is not included, such as a small corner shop, local church or minor roads. These are not separately mapped, rather they are treated as the infrastructure of the cell, similar to small blood vessels supporting living cells. The cell classification will include associated land such as the embankment of a motorway, the small piece of grass outside an office block, curtilage, etc. It is likely that in many cases there will be groups of cells with the same land use, such as groups of residential or industrial cells.

The cells have been grouped into broad categories which reflect their primary role within the economy, as shown in Table 1.

Table 1: CAST Cell Types

Neutral
1. Water
2. Non-Agriculture Vegetation
3. Brownfield
Residential
4. Residential
Transport
5. Roads
6. Rail & Metro Stations
7. Transport Interchange
8. Car Park
Service
9. Built Heritage
10. Health
11. Education

Service (continued)
12. Public Access Buildings
13. Military & Prison
14. Retail
15. Office
16. Built Leisure
17. Public Square & Pedestrian zones
18. Urban Green Space
Production
19. Industry & Warehouses
20. Agriculture
Other
21. Other
Mixed
22. Mixed

Attached to the cell type will be a range of attributes, covering population profile, economic activity, environmental quality and building levels and standards

CAST is a dynamic model of cities. The cells are interconnected across the city to allow for the population to seek work, gain and spend income, travel, etc. These produce a metabolism with in the cell and, in summary, a city wide metabolism. These processes drive the changes within the cells and the city.

CAST recognises that cities are open systems, so there are flows in and out of the city. There can be attractors outside the city boundary such as a large retail or population centres. In addition at a citywide level there are imposed rules and conditions. These can include planning policy which sets limits on height or density of buildings or the requirements for schools for a certain number of pupils. Also there are global actions such as the state of the world economy which, while not modelled with CAST, can be imported to influence actions within the cells.

Central to the operation of CAST is the fact that in general there are not many top-down imposed rules, instead the processes within the cells are free to evolve and co-evolve based on the rules within the cells. The key concepts come from Complexity Science where the patterns of the whole are greater than the sum of the parts and emerge from the processes within the parts. The city is made up of its cells but is greater than the sum of the actions in those cells.

As the actions of the cells are not centrally controlled, but are free to evolve depending on their internal processes and the influence of other cells, this allows a change in one cell to cascade and impact on other cells across the city. Cities are made up of a rich network of connections. People live in work in certain locations but their action spread across cells and have a rippling impact even on cells which they never directly visit. A change in one area of a city impacts on other areas of the city.

CAST aims to model changes in cities, concentrating in particular on changes to the economy, land use and transport. This integration of economy, at the cell rather than city wide level, is unique to CAST. Most models of cities assumes citywide economic patterns; ignoring that in fact while one part of city's economy may be expanding other sectors and areas can be in decline. Transport in CAST is also treated both as a land use and also as a real flow of people across the city.

While to capture the economic features and mobility of people is complicated and requires a significant amount of data and process rules, it also offers greatly enhanced understanding of the changes within a city and the opportunity to explore different scenarios of actions in development, planning, policy and infrastructure provision.

Most of the processes of CAST take place in the individual cells, this is their metabolism. The formulae of change and interaction will be replicated across all cells or all cells of the same type. However some processes take place across the city, often not primarily located within a cell or number of cells. To handle these CAST includes citywide flows and distribution boxes. Distribution boxes are used to collect and spend taxation, handle finances such as income for property (rent and mortgage) and provide loans to buy property, transport infrastructure and provision decisions, and the economic activity around construction and building maintenance.

There are several flows through the city such as transport, but the key one for CAST is the flow of money, the income of cells, gained through employment and from taxation, and expenditure on the many goods, services and taxation. This flow of money (fitness) connects the cells and drives the changes:

- increase/decrease in fitness of cells
- intensification/decline of current activity within cells
- change of use of cell type

The primary outcome that CAST studies is land use, the changes, expansions and contractions. Transport has a major influence both on the operating of the economy and of the uses of land. There are a number of subsidiary systems such as pollution, education/skills, population change, and household change and movement. These are mainly of concern in so far as they affect the metabolism and land use, rather than being studied themselves, but CAST can give outputs for changes in these systems. In addition there are the process with each cell, their internal metabolism (Fig. 2).

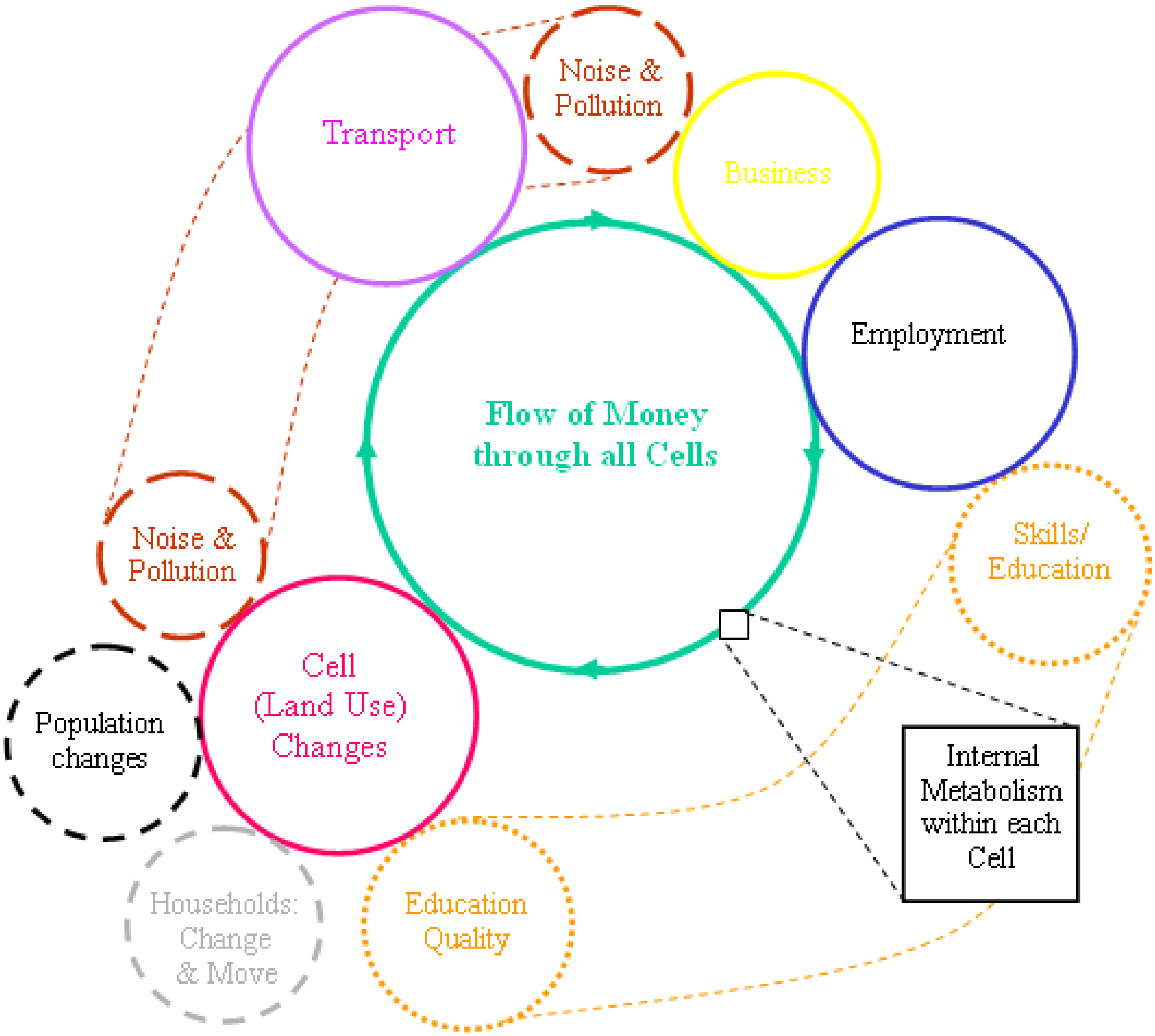


Figure 2 Flows in CAST

3.2 CAST model Implementation

In this section we explain the basis of the CAST method and key aspects of operation of the CAST software. The CAST model is based on 22 cell types, which all have a number of attributes and internal processes. These processes define the cell connectivity and transformation of inputs received from other cells into outputs, as well as internal consumption (metabolism) for each cell. The model is developed in Java and Java3D programming languages. The resolution of the model (the number of cells modelled) is specified on the command line, such as "java cast 130", which will run the model in the resolution of 130 x 130 cells. The cell size is typically 100 x 100 metres, which means that in 130 x 130 resolution CAST simulates an area of 13 x 13 kilometres.

In CAST, cells are open dissipative systems where rules are based on conservation of resources as follows:

Inputs = Metabolism + Reserves + Outputs (1)

as shown in Fig. 3.

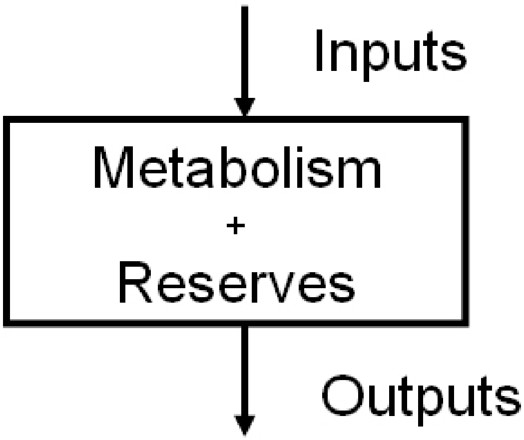


Figure 3 Conservation of cell resources

The cells are placed on a rectangular grid (Fig. 4), where they interact with other cells on the basis of connections between them and processes inside them. This method is based on Cellular Automata, with various extensions to allow non-neighbour connectivity as found in cities. The connections between the cells effectively form networks between the cells on the basis of characteristics of each cell. For instance, a residential cell will connect to an employment cell to get work and income, and to retail and service cells to purchase food and other goods, and obtain a range of services, including utilities, education, and others.

If the cell manages its budget well, the reserves will accumulate, and can be used for increasing the metabolism, or for expansion. We call these accumulated reserves the fitness of the cell.

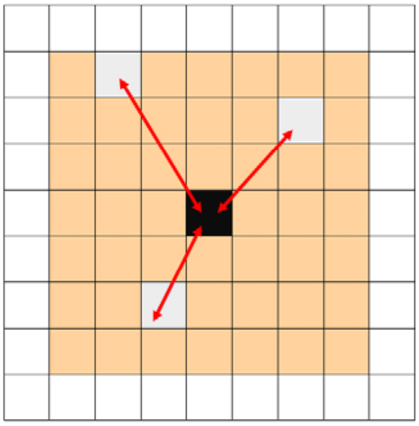


Figure 4 A rectangular grid in which land cells form networks for interaction with other cells

Economic modelling is achieved through differential market parameters between the city and the outside world. Thus, City GDP and World GDP sliders enable the user to set economic output, and inflation and reinvestment sliders determine how much of the output can be used to support growing population. Immigration rate into the city from the outside is determined as

$$\mathbf{I = f\ (GDP\ growth\ rate,\ birth\ rate,\ death\ rate,\ inflation\ rate,\ reinvestment\ rate)} \qquad (2)$$

Skill market sliders enable the user to set skill supply and demand levels inside and outside the city, which will modulate the immigration rate calculated in (2). Property market sliders enable the user to set differential supply and demand for property inside and outside the city, and the relationship between these parameters further modulate the immigration rate into the city. It should be noted that the immigration rate can be either positive or negative, representing an increase or decrease of city's population.

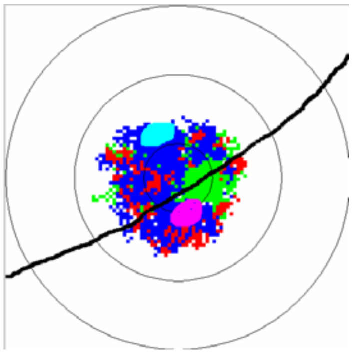
After the CAST software is loaded, it is initialised using external GIS data. The user can also supplement the GIS input by adding any of the 22 cell types using a manual input facility of CAST. Initialisation from external GIS files requires the files to be of a specific format.

When the user starts the simulation, cells start developing dynamically, based on individual rules on a cell level, and as result, a complex model of the city land use behaviour emerges. Using the graphical user interface, this behaviour can be displayed as a number of different attributes of cells, thus showing dynamic maps of cell types, cell resources/fitness, population, and various other attributes.

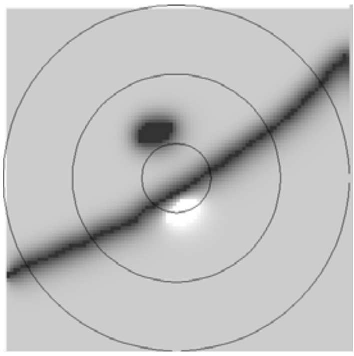
A three-dimensional view of these attributes is generated when a "View 3D" button is pressed. In this view, ground elevation as well as height of the cells is shown, where the latter is proportional to the value of the currently selected attribute. The 3D view is interactive, and enables the user to navigate the scene. This is similar to flying around the city and seeing not only the height of buildings, but also values of various attributes in the buildings, such as population, resources, quality of neighbourhoods, pressure for transport and others. Effectively, this represents derived GIS data, obtained as result of complexity based processes in the model. In the next section we show some example outputs from CAST.

4 RESULTS

We now present sample results of CAST operation in Fig. 5 a) to f). The first six sub-figures represent a randomly initialised city, and the seventh represents land use simulation based on external GIS data. Part a) of this figure shows CAST interface with cell expansion in progress and part b) CAST interface with attractors and repellents. Part c) shows road following, obtained as an emergent property of the model, and part d) expansion of the land use over time. Part e) shows two-dimensional land use with major and minor roads and part f) a three-dimensional interactive diagram of resources/fitness. Finally, part f) shows a dynamic simulation with GIS data from the Municipality of Oeiras, Portugal.



a)



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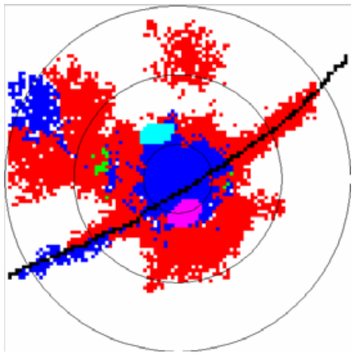

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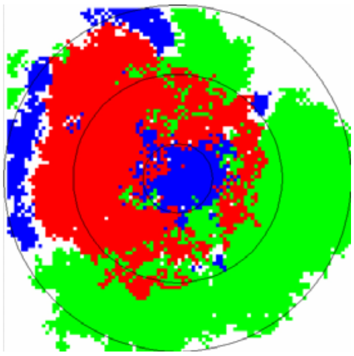

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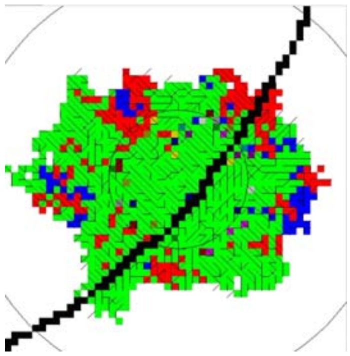

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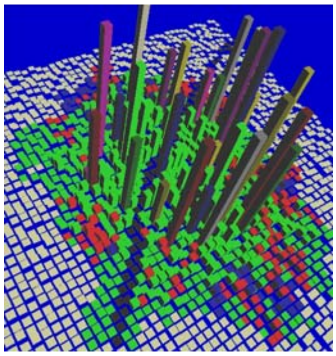
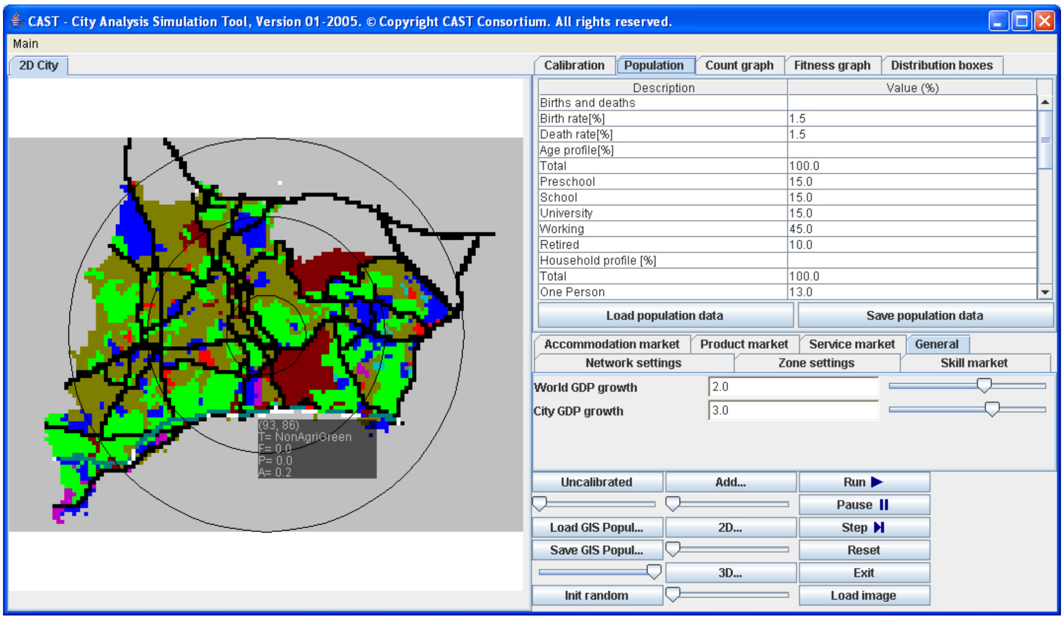


f)



g)

Figure 5 Examples of CAST output

Testing and calibration of the model was carried out using GIS data obtained from the Municipality of Oeiras. Shape files of land use were obtained for 1947, 1958, 1965, 1977, 1987, and 1996, and expansion rates of individual cell types based on the GIS data were first analysed. Subsequently, an auto-calibration process was developed and implemented. This process looks at the expansion rates of different cell types in GIS data and adjusts the parameters in the cells that regulate cell metabolism. The process was developed to work with data for two points in time in order to perform calibration. After the calibration was completed, data for one more point in time was used to perform validation. Specifically, data for 1977 and 1987 were used to perform calibration, and the results of software operation equivalent to 9 years after 1987 were compared with actual GIS data for 1996. By comparing the predicted and actual values it was found that predictions of residential expansion were very accurate (1.5% accuracy), predictions of industrial expansion were reasonably accurate (6.6%) and results of retail expansion were far less accurate. This lead to fine tuning of the software and continued work on validation and user testing.

5 DISCUSSION

Developing urban models that are useful for planners, politicians and the public face many challenges, including striving to simplify yet still represent the multitudinous processes within the city and their complexity. CAST aims to combine the concepts of Complexity to capture the dynamic and changing character of cities with the many layers of analysis used in rule based models. To develop such a model needs the combined experience of Complexity Science and urban processes, based on joint working of researchers and urban practitioners. CAST has taken this approach.

CAST aims to take forward the modelling of cities and by including many processes and factors previously not included in models based on Complexity it represents a step forward. In addition the collaboration between researchers and practitioners has strengthened this work.

However there are real challenges for CAST, some still not fully resolved. Deciding which processed to include and then to describe and represent them in the model is a major challenge as it is important to include the key factors shaping a city but not to so overwhelm the model that it is unworkable. There is a tension between representing the complexity of cities without making the model utterly complicated. CAST has focussed on the economic, land use and transport processes within the city and given little regard to many social and cultural features that can also have a significant impact. This remains a challenge for future development of CAST, in terms of necessary data, processes and interactions.

6 CONCLUSIONS AND FUTURE WORK

We described here our research into city modelling based on principles of Science of Complexity. Unlike other models of the similar kind which address particular aspects of city development and ignore others, CAST attempts to integrate land use, economics, transport, and population dynamics. There are several market mechanisms deployed in CAST, enabling the user to specify differential parameters between the city and the outside world. These market mechanisms influence population dynamics in the city which in turn provides indication of transport demand. CAST can be described as a network model of the city, where connectivity between different cell types and their individual metabolism determines the cell behaviour and the behaviour of the overall system. Like in the real city, sparse connectivity will result in slow economic performance, and supra connectivity will result in chaotic performance. In CAST, connectivity, population and market parameters can be controlled by the user, thus helping to investigate different behaviours of the city under different scenarios.

CAST is being developed in collaboration between researchers, urban practitioners and computer scientists, and thus is a truly multidisciplinary project addressing multidisciplinary issues. Although there are some future challenges ahead in terms of streamlining the existing economic and other processes in cells and networks, CAST is already giving some encouraging results and has a potential to become a versatile analysis and decision making tool for urban practitioners.

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