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PROCEDURAL LOT GENERATION FOR EVOLUTIONARY URBAN LAYOUT OPTIMIZATION IN URBAN REGENERATION DECISION SUPPORT

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SUMMARY: *Decision support in urban regeneration planning involves fulfilment of complex design objectives that require a close collaboration between stakeholders, designers and planners. The objectives are to achieve computationally optimized design plans that are environmentally robust and sustainable. For the purpose of pre-planning analysis and optimization of such design models, the construction framework of the whole system development life cycle is simulated using specialist analysis tools. In the analysis and design phase of such a construction process, location allocation of built environment structures integrated with AI based urban assessment models remain a cumbersome task. With the advent of sophisticated computing hardware and 3D modelling techniques, it has become viable to visualize and develop simulation outcomes with ease over standard computers. However, creation of simulated outcomes with huge urban details still remains a daunting task. With the advent of knowledge-based data standards and mining techniques, possibilities have arisen to integrate procedural urban modelling frameworks with socio-economic deprivation assessment systems to create massive city models in order to improve sustainability and smart growth. The implementation of a procedural modelling framework offers a promising area of research in location allocation optimization of residential and public service structures for urban regeneration planning and collaboration purposes but is still largely stochastic in nature until now.*

The work presented in this article proposes an L-system-based automated urban layout generation module in addition to an evolutionary building placement optimization system for the purpose of urban regeneration decision support. The location allocation optimization of a highly accessible pedestrian and street network grid still remains a complex process especially with neighbourhoods suffering from severe socio-economic deprivation. Using an extension to 'L-systems', the module utilizes an 'mBPMOL' system to recursively subdivide an urban regeneration layout and later encode the layout to a genetic chromosome to iteratively place a range of urban structures to the lots. Moving further, the system implements a distance-based socio-economic deprivation minimization fitness function and assesses subsequent individual genetic solutions to search for an optimized layout.

The development of such an online procedural framework is a very first attempt to employ the capabilities of procedural automation with evolutionary computation to automatically generate and optimize the placement of a large number of building models. The outcome achieved a set of relatively optimal solutions with evaluation based upon a distance-based fitness objective function of various public service structures. The solutions (layout *plans) thus obtained offered a number of moderate to highly accessible alternatives. Development of such a system is meant to facilitate decision support and improve time efficiency among urban designers and planners.*

KEYWORDS: *Artificial Intelligence, Genetic Algorithms, Urban Regeneration, Built Environment, Urban Planning.*

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1. INTRODUCTION

The renewal of the inner city built environment areas has become an important facet of the construction and regeneration industry. Despite a range of progression steps taken out for the last decades of urban regeneration in the western world, particularly in the UK, many urban areas still face problems ranging from crime, unemployment, health and wellbeing, and public service access to a dilapidated social and economic infrastructure. A great number of areas that are taken into consideration by regeneration partnerships contain a disproportionate number of poor masses with a high level of social, environmental as well as physical deprivation. Planning and development of additional built environment structures or residential schemes within such schemes require a thorough and in-depth analysis of socio-economic as well as environmental factors affecting the neighbourhood of such areas. With the availability of a number of built environment variables (crime, accessibility, employment, health, etc), the issue of location allocation of various public service structures in order to mitigate the neighbourhood deprivation turns out to be a complex, multi-objective optimization problem. Consequently, the overall outlook of the rehabilitation of such areas creates a decision-making nightmare for urban planners as well as stakeholders.

Decision support simulation software generally does provide a level of assistance to planners but are largely restricted to desktop based simulation tools which lack significantly, if not entirely, in terms of providing a well integrated and networked platform. Procedural synthesis of urban form to automatically create built environment domains started only recently with the work from Parish and Muller (2001). The idea was initially introduced by Stiny and Gips (1972) for shape generation using shape grammars that eventually inspired the modelling of plant growth by Prusinkiewicz and Lindenmayer (1990) termed as the L-systems. Lately, L-systems are widely used to introduce automation in complex real-world systems. The ability to draw and interact with massively built city structures and attributes promises to be a valuable domain in the field of recreational cityscape development (Watson *et al.,* 2008), road network planning (Chen *et al.,* 2008), urban scene rendering (Coelho *et al.,* 2003) and procedural modelling of buildings (Muller *et al.,* 2006). However, manual drawing of such urban environments is a very time consuming task particularly if a realistic level of variety in cityscape modelling is sought. The situation gets further complex if the outcome of such massive urban domain is subject to dynamically change its layout with respect to outcomes from artificial intelligence routines and simulation modules.

With the advent of state-of-the-art information and communication technology (ICT) disciplines, such as high speed internet, computer aided design (CAD) automation and sophisticated artificial intelligence (AI) routines; the modelling and sharing of highly rendered graphical models have become a viable choice in decision support (Verbree *et al.,* 1998; Nariman *et al.,* 2000). Yet, the scope of such decision support software limits itself to desktop-based simulation tools to a great extent due to lack of integration with recently developed online virtual modelling standards such as virtual reality modelling language (VRML) and X3D. Integration of these standards in order to simulate AI modelling outcomes over mere internet browsers is expected to fill a significant gap within the domain of ICT based smart graphical modelling in construction automation.

This paper presents the implementation of a procedural urban planning layout generation model to provide a front-end for a placement optimization module for a range of public service structures and residential units planned for regeneration schemes. The outline of the paper is as follows: Firstly, related research in the field of urban development patterns and relevant transport issues is discussed and an integration gap to decision support modelling is presented. Further to this, a review of current visualization literature and procedural modelling based systems is elaborated and the scope of the work presented is formalized. Finally, the development of a genetic algorithm (GA)-based location-allocation algorithm and the relevant outcome is presented based upon a deprivation assessment model.

2. URBAN LAND USE AND TRANSPORT MODELLING VISUALIZATION

Transport and land use planning have been inter-related for almost half-a-century to establish transit-oriented development where higher-density, mixed use areas are constructed around centralized transit systems. Conventionally, design planning of vacant regeneration districts starts with a robust lot assignment, road layout generation and structure location assignment of various public services such as primary school, shopping centres, post offices, etc. In any urban design, the layout of general traffic thoroughfare is the principle structuring element that acts as the basis of sustainable urban design layouts. As a result, neighbourhoods with a weak inter-connectivity to the adjacent districts or transport nodes are considered socially excluded and bear significant socio-economic deprivation on their residents. On the contrary, vicinities with safe and well-connected design plans promote an environment where people are able to walk or cycle to basic public services such as retail outlets, healthcare and employment services (Aytur *et al., 2008)*. In addition, provision of a robust cycling and pedestrian infrastructure in neighbourhoods increases the likelihood of people to engage in physical activity (Dill and Carr, 2003). Visual aspects of the surrounding construction (Foltete and Piombini, 2007), travel and land-use mix integration (Bertolini *et al., 2005)* are also considered paramount to the general "walkability" of an area. Furthermore, availability of public transport alternates such as transit/metro and bus stations accessibility have a positive effect over the health of resident individuals (Stokes *et al.*, 2008). An increased reliance on public transport tends to reduce personalized automobile usage which is considered a major contributor of atmospheric emissions affecting the general wellbeing of the residents and the subsequent habitat loss and ecological destruction (Brisbon *et al.*, 2005).

Pertaining to these socio-economic and environmental design attributes, the measure of travel in an area is generally divided into three particular levels of accessibility: travel in the local areas for family-oriented purposes, such as grocery trips, termed as area mobility, travel done by individuals for individual purposes, such as university/employment trips, termed as individual mobility and the overall mobility of the residents of an area (Preston and Raje, 2007). Out of these three levels of accessibility, the "area mobility" is generally regarded as the one which could be done without excessive reliance on personal vehicular transport if replacement provisions that encourage walking and public commuting are provided. Duany (2002) presented six models that constitute a range of options with variable impacts on the economic, environmental and physical wellbeing of residents. The first five patterns bear a "web structure" form whereas the sixth form – the Radburn shows a "stem pattern" as shown in Fig. 1. The Radburn pattern generally offers appeal to pedestrian friendly neighbourhoods and localized traffic patterns but has a disadvantage of traffic congestions due to an absence of interconnectivity. The webbed patterns shown from b – e does offer a great deal of connectivity but bear individual drawbacks. The Nantucket (b) and Washington (d) patterns suffer from an uncontrollable variety of lots which makes it harder to uniformly provide space for residential and mixed use development and provide equal access to services for the community. Mariemont (c), Washington (d) and Riverside pattern (e), provide a central boulevard for commercial lots and office space to ensure feasible pedestrian/cycle access. However, these patterns appear to be highly disorienting, thereby making a robust network and traffic plan infeasible. The Savannah pattern (a) is remarkably known for its adjustable lot depth, traffic control by design, increased driver visibility, even traffic dispersal, better parking provision and utilities access. Though suitable for creating quiet neighbourhoods with recreational open space, this scheme suffers from a monotonous design and may not easily adjust to changing terrain like hills, water bodies, etc.

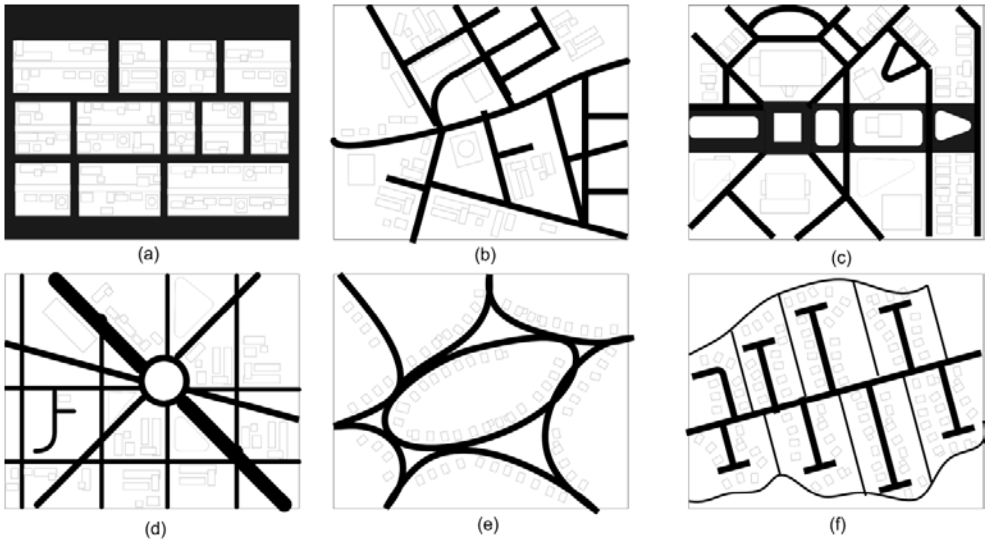


FIG 1: Urban structure thoroughfare patterns with variable environment impacts due to specific design attributes (a) Savannah Pattern, (b) Nantucket pattern, (c) Mariemont pattern, (d) Washington pattern, (e) Riverside pattern, (f) Radburn pattern.

Adoption of any of these patterns in the design planning of a regeneration scheme largely depends upon the immediate circumstances of the neighbourhood. Regeneration schemes carried out within neighbourhoods suffering from atmospheric emissions due to high traffic congestion generally require a "web structure" street layout to ease the traffic flow. On the contrary, regeneration schemes that require allocation of public services that put emphasis on traffic calming measures such as schools and hospitals generally prefer Radburn (stemmed) pattern of street layout in order to discourage personal transport and increase a general walk-able access to amenities (Newman and Kenworthy, 1996; Stead, 2004).

Traditional urban simulations for street design automation are devised as a combination of spatial interaction models, discrete choice models and the basic functional/representational logic. However, the traditional modelling techniques are limited in a manner that the urban form realization tends to start from a macro to micro level. One of the major collective efforts contributed to urban spatial modelling was initiated by Paul Waddel's team in the Department of Urban Design and Planning at University of Washington, US. The model – UrbanSim, as a set of interacting sub-models for demographic and economic transitions, household and employment relocation and choice, real estate development and land prices. The model so far has incorporated and analyzed areas including, but not limited to metropolitan transport planning (Waddell *et al.,* 2007), urban development and environmental impacts (Noth *et al.,* 2003) and compact development and transport investments (Waddell and Borning, 2004). In the area of discrete urban modelling, cellular automata and multi-agent systems offer great potential for decision support tools in urban and transport planning with their capacity to simulate individual entities and units in a flexible manner. Most commonly used approaches in discrete urban modelling are based on cellular automata (CA) and Multi-agent Systems (MAS) (Geertman and Stillwell, 2002). CA has been used in numerous applications of urban planning and geography focusing on dynamic and non-linear properties of urban growth processes including spatial decision support-based systems (Stevens *et al.,* 2007), 2D suburban and rural residential patterns (Caruso *et al.,* 2007), agent-based residential development Li and Liu (2007), architectural design processes Herr and Kvan (2007) and mobile agents based transport models (Puliafito, 2007). Multi-automata CA integration of different environmental systems (Fonstad, 2006), error and uncertainty rectification in urban modelling (Yeh and Li, 2006) and land use forecasting (Tonino *et al.,* 2002) are also considered active areas of investigation in CA based research. Herr and Kvan (2007) recently contributed a regenerative design process in architectural designing with a degree of repetition present. Yet, these models generally lack macro-level realization of simulation outcomes and to date there has been no significant effort in the integration of 3D modelling outcomes with the current state-of-the-art internet-based visualization technologies.

3. SIMULATING URBAN MODEL OUTCOMES WITH VIRTUAL REALITY (VR)

With the advent of sophisticated computing and graphics hardware, it has become viable to visualize real-world simulation outcomes over desktop-based VR systems. VR technology allows a user to interact with a computer-based simulation model without actually being present in the real situation. With the use of three dimensional computer graphics, interactive devices and high-end computing machinery; it is now possible to render, simulate and manipulate real-world objects in real time (Nomura and Sawada, 1999). In a geographic perspective, VR plays an important role in landscape visualization and presentation. Investigations of public's interest into photorealistic landscape visualization shows promising prospects for 3D visualization. In landscape planning there is an increased expectation among planning organizations of the future prospects of 3D visualization in planning and visualization (Paar, 2006; Daniel and Meitner, 2001; Bryan, 2003). This has given way to 3D reconstruction techniques to emerge as an evolving area of research in photorealistic model construction. In a subsequent domain, Alves and Bartolo (2006) developed a rapid 3D prototyping system for historic buildings using the biological perception of human vision as its very basis. Similar areas in pure GIS perspective have also been explored for 3D topological modelling (Germs *et al.*, 1999; Huang and Lin, 2002; Verbree *et al.*, 1998*;* de la Losa and Cervelle, 1999), object orientated integration of 3D GIS (Dollner and Hinrichs, 2000) and integration of digital terrain and building models (Zhou *et al.*, 2004). The integration of 3D visualization into GIS further extends the role of cartographic information representation and sharing. The GIS/VR hybridization has been implemented in a wide variety of research applications ranging from landscape visualization (Wu *et al.*, 2008); to archaeological workflow modelling (Katsianis *et al.*, 2008*).* With the extent of synchronous collaborative virtual environments the interest has shifted into the use of VR as a replacement or extension to collaboration using CAD systems for a broad range of industrial applications (Nguyen and Selmin, 2006; Rosenman *et al.*, 2007).

However, the majority of such implementations are limited to visualization only and lack in terms of remote collaboration and user interactivity. With the introduction of robust telecommunication technologies, it is now possible to initiate remote customer/client collaboration in industrial prototype evaluation. This is generally made possible with the employment of presentation concepts of virtual reality in industrial applications (Di Gironimo *et al.*, 2006). Yet, being extensively physical systems, the deployment of all these techniques, including the VR, have their own limitations in visualization applications. That is, computer-based urban planning models generally comprise of millions of polygons. Real-time visualization of highly detailed and massive systems generally induces a significant performance lag due to the current computational limitation of software interfacing of VR systems (Jones, 1996, p.121). Until recently, shortcomings in streaming data transfer over mediums such as dialup internet and radio-links remained a major hindrance in the propagation of real-time data. Yet, these limitations opened a significant area of exploration within the domain of the generation of graphical mass-models of huge urban built environments, and that was, the development of online 3D modelling frameworks.

3.1 Standardization of web-based 3D modelling of complex systems

During the past two decades, with the introduction of high speed internet technologies and online 3D modelling standards, the concept of complex visualization for contemporary applications shifted to web-based VR visualization systems. Along with several VR modelling approaches, X3D is the ISO standard for interactive 3D developed by the Web3D-Consortium (2007) as a successor to Virtual Reality Modelling Language (VRML97). The standard was introduced for communicating real time, interactive, 3D content for visual effects and behavioural modelling. It has now been widely used in numerous domains across various hardware devices and a broad range of applications including prototyping, simulation and visualization enabling incorporation of 3D data into non-3D content. Also, being considered a successor to VRML, the standard's XML support makes it easy to expose 3D data to web-services and distributed applications, providing it a prime leverage over other desktop based modelling tools and VR applications. Furthermore, X3D's underlying framework makes it possible to support large environments such as cities through level-of-detail (LOD) nodes. Since, the framework is primarily meant for web delivery, it allows very large spatial models to be handled and viewed on distributed servers and a limited number of clients (Leeuwen and Timmermans, 2004, p.78). To date X3D is being utilized in a vast majority of applications including discrete event simulations (Ouerghi, 2008), rigid body dynamics (Engström, 2006), education and training (Ieronutti and Chittaro, 2007), GIS (Hetherington *et al.*, 2006), procedural 3D object generation (Murphy, 2008), virtual urban modelling (Coelho *et al.*, 2003), architecture and archaeology (Meyer *et al.*, 2008) and haptic and medical simulation.

The flexibility of X3D to objectively simulate real-world situations over mere internet browsers without any third-party software support makes it a suitable domain for applications that require online, networked display of spatio-temporal data. The technology has not yet been fully exploited in the procedural domain for generating massive urban models in order to provide real-time presentation and manipulation of model outcomes. Therefore, introduction of an online spatio-temporal platform that is able to visualize planning AI/model simulation outcomes for collaboration and decision support purposes would fill a major gap in the integration of industrial and research sector organizations thereby promoting faster knowledge transfer possibilities. However, the ultimate question still remains, and that is, how to graphically develop urban neighbourhoods containing thousands of uniquely built structures without bringing-in the slow-paced human modellers to develop the simulation outcomes. The problem is efficiently resolved by means of procedural shape automation with the help of specialist grammars and a set of rules.

3.2 Procedural mass modelling in built environment

In spatial visualization, displaying and manipulating 3D models in real time for environments as huge as city centre layouts is a computationally intensive process. Laycock and Day (2003) investigated the existing methods for rapidly generating models of real scenes focusing on the reconstruction of urban models. The work eliminated the conventional, time consuming modelling applications such as 3D Studio Max and CAD for modelling purposes and emphasized over a sensor-based modelling framework. The two promising domains discussed in this work used multiple view geometry and domain specific modelling. The first approach had its drawbacks in being overly user dependent in terms of feature extraction and thereby faced problems in model recovery. The second method did follow an unsupervised approach but lacked in generating accurate outcomes of model shapes.

These shortcomings were addressed by the usage of advanced graphics concepts of shape grammars and fractals to produce realistic and highly rendered urban mass models. The approach, known as procedural modelling, is generally accompanied with probabilistic grammars to induce the required degree of realism in 3D mass modelling of cities. Assembly of such models follows specific shape grammars which belong to a class of production systems that produce geometric shapes not stored in the computer previously. The grammars consist of shape rules and a generation engine that select and process a set of rules. Such a production system, in general, comprise of a minimum of three shape rules: a start rule, a fundamental rule and a termination rule. In the context of buildings, the production rules initiate a process by first creating a crude volumetric model of a building which is often termed as a “mass model”. The methodology then continues with the relatively finer details of building facades and eventually moves in to finest details of windows, doors and other visual features.

The idea of using such production systems to model urban environments using shape grammars was initially investigated by Parish and Muller (2001). The system named as CityEngine created a complete city to the degree of generating traffic network and buildings where each building consisted of a simple mass model and shaders for façade details. Following suit, Muller et al. (2006) demonstrated a novel methodology of generating geometric details on facades of individual building structures. Muller used procedural modelling to create huge urban environments primarily for the graphical regeneration of pre-historic cities and generic mass residential neighbourhoods. The authors used a specialized shape grammar (CGA Shape) for the modelling of massive urban layouts. The shape grammar iteratively implemented production rules that evolved a design by gradually adding graphical details to a 3D environment. The work is claimed to be the very first effort to address volumetric mass modelling and roof design. The approach describes rule implementation for the combination of shapes using control grammars and stochastic rules. The procedural methodology has been further elaborated to cater for housing interiors by Martin (2005). The work, instead of emphasizing building exteriors, started with housing interiors and used it to define the exterior model of a building infrastructure. The resultant system was able to robustly generate 50,000 houses in less than 3 minutes. To date, such systems have largely been limited to stochastic rules and therefore lack significantly in terms of integration with artificial intelligence (AI)-based decision support. Foremost, the most significant work done in the domain of street network modelling was by Chen *et al.* (2008). The work used tensor field design to efficiently model the generation of a graph and interactive editing of street modelling. However, the work only modelled a single level spatial resolution and a stochastic generation system.

Nonetheless, a great majority of work done in the domain of procedural mass modelling is an extension of the biologically inspired methodology known as the L-systems. The methodology was initially introduced by Prusinkiewicz and Lindenmayer (1990) to simulate plant development. The core idea was to utilize the positional information of a plant structure that related features of a plant to their position along plant axes. The procedural approach followed in the work removed the tedium of specifying and placing each plant component individually. The idea remarkably matched with a vast range of real-world systems that followed concepts of street layouts, fluid dynamics, hierarchical routines and biological growth. As a result, the idea has now been widely used in many domains of medical graphics, animation and film industry, urban planning, etc.

3.3 Theoretical framework and application of string rewriting L-system

In theoretical computer science and mathematical logic, string rewriting systems (SRS) are extensively used in applications that require replacement of sub-terms of a formula with other terms based over a set of logical rules. The usefulness of these systems, lies in their ability to depict graphical objects that contain a degree of ‘divisible repetition’ similar to that present in human arteries or plant branches. OL system is a similar, parallel rewriting system that is used to iteratively develop 2D/3D real-world figures and shapes using primitive drawing objects such as lines, planes, cubes, spheres, etc. Such production OL systems are generally context free and are not concerned with the context in which the predecessor appears. A context-sensitive OL system, on the other hand, makes it possible for grammars to avoid, for example, the placement of doors on higher floors in 3D building model generation or street placement very close to major junction in case of 2D road layout generation.

For any such system implementation let V denote an alphabet, V^* the set of all words over V and $\mathrm{V}+$ a set of all non-empty words over V. A String OL-system is an ordered triplet $\mathrm{G} = [\mathrm{V}, \omega, \mathrm{P}]$ where V is the alphabet of the system, $\omega \in \mathrm{V}+$ is a non-empty word called an ‘axiom’ and $\mathrm{P} \subset \mathrm{V} \times \mathrm{V}^*$ is a finite set of productions. A stochastic OL system is an ordered quadruplet $\mathrm{OL}_{\rho=}[\mathrm{V}, \omega, \mathrm{P}, \rho\ ]$ and function $\rho: \mathrm{P} \to (0,1)$ is the probabilistic distribution that maps the set of production probabilities. The assumption is that, for any letter $\mathrm{a} \in \mathrm{V}$, the sum of probabilities of all productions with the predecessor a is 1.

The example shown in Fig. 2 (a) employs a node rewriting algorithm to recursively subdivide tile PQRS into two tiles PQUT and TURS where the lengths of the edges form the proportion:

$$^{\mathrm{p}}/_{\mathrm{q}} = {}^{\mathrm{q}}/_{\left(\frac{1}{2}\right)\mathrm{q}}$$

The above equation implies that $q = p\ /\ (\sqrt{2}q)$. The tiles are connected by a branching line specified by the following L-systems where the angle of increment was set to $\delta = 90^0$:

$define\ \#\ R\ 1.456$

$$\omega = A(1)$$

$$p_1: A(S) \to F(S)[+A(^S/_R)][-A(^S/_R)] \tag{1}$$

The L-systems shown in equation (1) operate by appending segments of decreasing length to the structures obtained in the previous derivation steps. Once the segment has been integrated in the system, its length does not change. However, being a node-rewriting system, this methodology does not keep a trace of sub-divided tiles (lots) specific to the problem domain of urban lot assignment for regeneration schemes and therefore cannot be directly applied. Transport systems similar to those discussed as “webbed” patterns in Section 2 can efficiently be described by graphs with cycles. The grid-based cellular layout of urban lot mimic to a great deal with the depiction of the cell division patterns expressed using the formalism of map L-systems which allows for the formation of cycles within a structure.

Mathematically, such cellular layers can be represented using a class of planar graphs with cycles, called maps as given by Tutte (1984). Within the domain of lot assignment in urban planning, the concept can be understood by the characterization given by Nakamura in Rozenberg *et al.* (1986, pp. 323 - 332):

- A map is a finite set of regions (or lots) where each region is surrounded by a boundary consisting of a finite, cyclic sequence of edges (or roads) that meet at nodes (or junctions)
- Each edge has one or two nodes associated with it where one node (vertex) case occurs when an edge forms a cycle (or cul-de-sac).
- Every edge is part of the boundary of a region (or lot).
- The set of edges is connected and there are no islands within regions (there are no sub lots within lots).

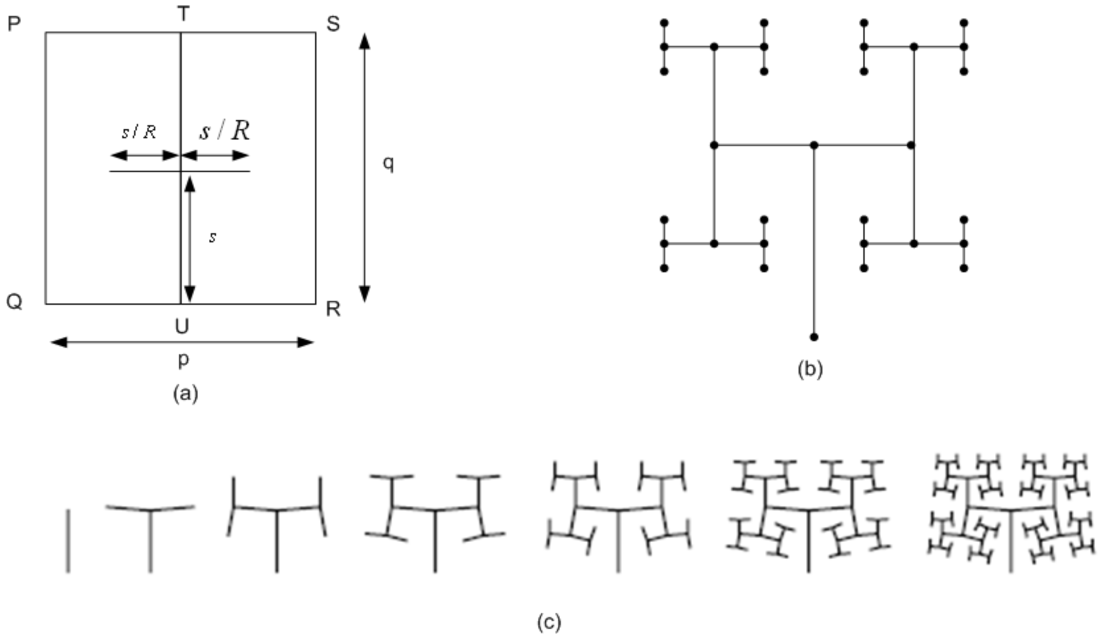


FIG 2: (a) Tiling related to a space filling branching pattern, (b) Branching pattern generated by the L-system specified shown in (a) with angle increment of $\delta = 90^0$ *(Bottom) Branching pattern generated by the L-system specified shown in (a) with angle increment of* $\delta = 85^0$

4. PROCEDURAL ROAD LAYOUT AUTOMATION FOR EVOLUTIONARY LOCATION ALLOCATION OPTIMIZATION

To model a virtual urban regeneration plan, a regeneration map has to be designed as a first step in the structural lot assignments. A simple procedural approach based on L-systems was used to create a road map to act as a base layer for the initial population of solutions input to evolutionary genetic algorithms (GA). The initial placement starts with the procedural placement of a randomized road layout over a vacant cell-based urban district. The technique uses a modified form of Map L-Systems called ‘mBPMOL’ (mBPMOL) systems in order to obtain variable sized lots along with a stochastic road network suitable for the placement of various regeneration structures and public services. ‘mBPMOL’ systems were as introduced as a refinement of the basic concept of map L-systems by Nakamura as cited by Rozenberg *et al.* (1986, pp. 323 – 332) in Prusinkiewicz and Lindenmayer (1990). The procedural modelling-based GA solution implemented in this work develops a randomly generated family of individual chromosomes (a generation). The goal is to provide a baseline of solutions to start the genetic run (fitness test) with. The initial generation consists of 30 randomly generated chromosomes (or urban layouts) which are tested against an accessibility deprivation-based fitness function. The theoretical background of GA is discussed only briefly in the next section as it is out of the scope of the work presented.

The string rewriting system discussed in Section 3.3 was further extended to the concept of parallel rewriting of forms that mimic cell division. Generally, such rewriting systems operate either sequentially or in parallel. These can be region controlled or edge controlled. Since, the scope of this work of dynamic lot assignment is primarily related to control the lot division; the region controlled methodology was preferred for the layout generation algorithm that assigned labels to recursively dividing regions. Since the scope was to build structural details in each lot while keeping each lot independent of each other, a context free system was required which suggested the use of Binary Propagating Map OL Systems with Markers.

4.1 'mBPMOL' systems for urban layout generation

A parallel map OL-system (mBPMOL) is a parallel rewriting system that operates to create independent maps (or lot regions) that are context free i.e. each region is created irrespective of the neighbourhood regions. The system operates in a binary fashion and can therefore divide a single cell (lot) into a maximum of two child regions. The lot division may continue until the desired minimum lot size is achieved. Such systems propagate in a manner that the division occurs with an edge (road/pathway) in the middle, which connects the surrounding edges (or roads); this splits the labelled parent region into two child halves proportioned by some set criteria.

A definitive explanation of edge-controlled mBPMOL systems is given in Prusinkiewicz and Lindenmayer (1990, p.146). This is modified as a region-controlled technique where an mBPMOL ξconsists of a finite alphabet of region labels Σ (instead of edge labels), a starting map $\omega(1)$ with labels from Σ and a finite set of region productions P given in (3) and (4). For the current scope of work only two production rules were used and implemented as shown in Fig. 3.

The example shown in Fig. 3 employs an 'mBPMOL' map rewriting algorithm to recursively subdivide area A and B into two areas AB and A as shown in where the areas of the maps form the proportion:

$$\mathrm{A(a)} \,/\, \mathrm{A(b)} \;=\mathrm{A(b)} \,/\, ((\mathrm{R} \times \mathrm{A(a)}\,)\,)$$

$$\mathrm{A(a)} = \sqrt{}\mathrm{R} \times \mathrm{A(b)}$$

Here R is a random number depicting the seed position to divide the production for next rewriting shown by a greyed path in Fig. 3 ranging from 0.4 to 0.6.

$$\omega \rightarrow AB \tag{2}$$

$$p_1 \colon A \rightarrow AB \tag{3}$$

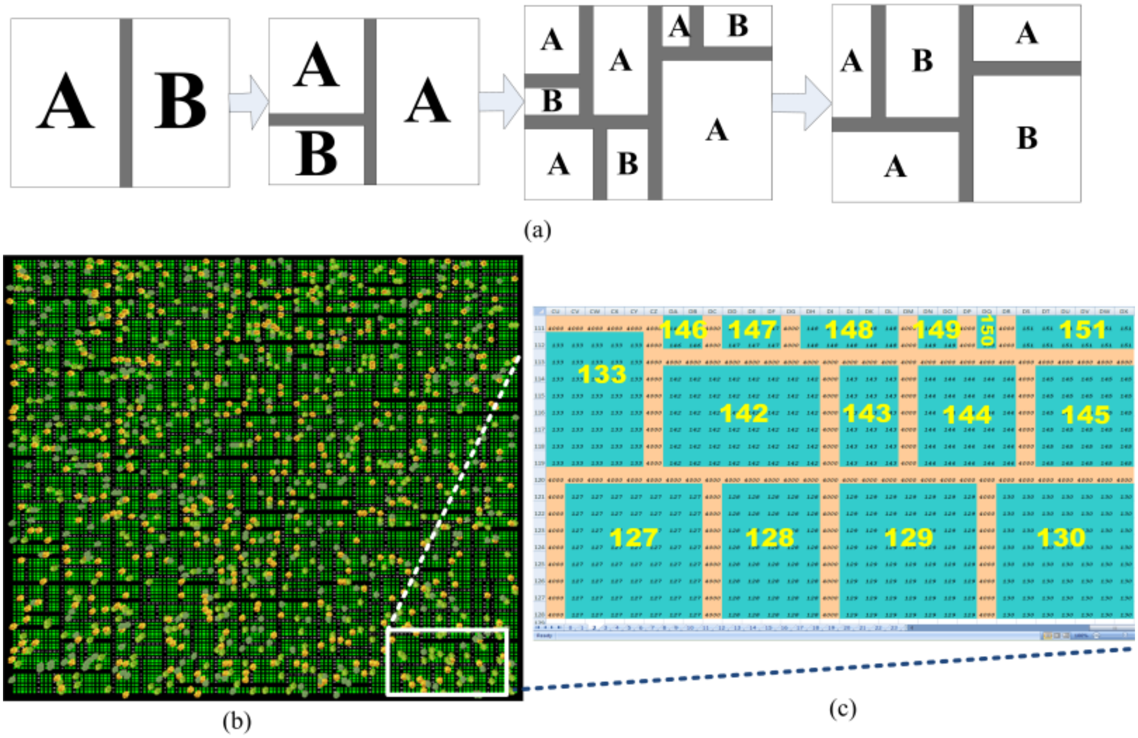
$$p_2 \colon B \rightarrow A \tag{4}$$

In the scope of this work, a map is actually a regeneration plan where each cell is a lot of specific size and edges represent roads. An example of such a Map L-system is shown in Fig. 3 with undirected edges where each production is of the form $\mathrm{A} \rightarrow \alpha$ where the neutral edge $\mathrm{A}\epsilon\Sigma$ is called the *predecessor* and the string α, composed of symbols from Σ and special symbols $[,], +, -$ is called the *successor*.

4.2 Application of production rule for automated layout generation

The production process starts with a single *map* or urban plan layout called *axiom* as shown in Fig. 3 and starts as follows:

1. Select the currently active layout with symbol A in the set; Apply initial label
2. Choose a production rule with symbol A on left hand side in order to compute the successor for symbol A; label the resulting two labels consecutively as new set of maps ANEW,
3. Add ANEW as current to the setup and continue with Step 1 until the minimum lot size is achieved



(a)

(b)

(c)

FIG. 3: Context free mBPMOL based stochastic split grammar for randomized lot assignment/road layout generation as an initial base for first generation chromosomes

Production rules are defined in the following form:

$i: \text{predecessor}: \alpha \rightarrow \text{successor}: \rho$

Where i is a unique identifier for the rule, *predecessor* $\epsilon\ V$ is a symbol identifying a lot that is to be replaced with *successor*, and α is a logical condition that has to evaluate to true in order for the rule to be applied. The symbol ρ is the probability for the rule to be applied which is kept equal to 1 for this work. The logical condition for layout splitting algorithm is the minimal area in square meters for the lot i. The procedure's recursive algorithm is given in Table 1 follows:

TABLE 1: *A pseudo-code for the ‘mBPMOL’ based recursive routine for the generation of layout shown in Fig.3*

```
$i = 0, j = 0$
$M = columns$
$N = rows$
$recurproduction\left(L, Cl_i, Cl_M, R_{w_j}, R_{w_N}\right)$
$Begin$
$If\ (area_L \leq T_{min})\{$
$return\ False$
$\}$
$else\ \{$
$If\ Cl_{width} \geq Rw_{width}$
$seed = rn \times (\Delta Cl)$
$recurproduction\left(L, Cl_i, Cl_M, R_{w_j}, seed\right)$
$else\ if\ Cl_{width} < R_{width}$
$seed = rn \times (\Delta R_w)$
$recurproduction\left(Map\ m, Cl_i, Cl_M, seed, R_{w_N}\right)$

$recurproduction\left(L, seed, Cl_{fin}, R_{w_{init}}, R_{w_N}\right)$
$return\ L$
$\}$
$End$
```

Procedural building algorithms are known for their stochastic rule-based model generation as evident from this section. Such a probabilistic building generation may prove useful for animation and archaeological purposes but lacks in providing decision support for planning and optimization. For example, iterative placement of variably designed single-story or detached houses may give a sense of urban surrounding; it can hardly be employed to build an intelligently planned urban plan without a smart lot assignment of various public services such as schools, GPs, post offices, etc within the immediate residential locality. As discussed earlier, automation in urban planning has been an area of research which has not yet exploited AI based optimization to its fullest extent.

4.3 Integration of procedural model layouts with the GA for layout optimization

Henceforth, the article discusses an evolutionary placement optimization methodology of a range of housing schemes and public services over a procedurally developed urban mass-model using a genre of AI routines known as genetic algorithms (GA). GA is a search technique to find exact or approximate solutions to problems. It originates from the basis of the theory of evolution. GA became popular through the work of John Holland in the early 1970s and particularly his book “Adaptation in Natural and Artificial Systems” (Holland, 1975). A GA is an iteratively recurring procedure which borrows the basic principles of natural selection and survival of the fittest from natural evolution. An implementation of GA begins with a population of (typically random) abstract representations (called chromosomes) of candidate solutions (called individuals) to an optimization problem. The population subsequently evolves towards better solutions in an iterative fashion while selecting and promoting better individuals and eliminating the least good ones. In a broader usage of the term, GA is any population based model that uses selection and recombination operators to generate new sample points in a search space. Since it searches from a population of such points, not just one point, the probability of the search getting stuck in a local minimum is limited. GA start its search by random sampling within the solution space and then use stochastic operations to direct a hill-climbing process based on objective function values (Mitchell, 1998).

In GA terminology, a solution to a problem is an individual called a chromosome and a group of existing solutions at each stage is a population. Each time a new population of individuals is created, it is called a generation. A chromosome is formed of alleles - the binary coding bits. The fitness of any individual corresponds to the value of the objective function at that point. Genetic operators termed as selection, crossover and mutation are responsible for the control of evolution of generations of problem solutions.

4.3.1 Encoding procedural models to genetic chromosomes for fitness evaluation

As per the objective of this research, before the commencement of a genetic run, the procedurally generated layout must be encoded to a binary representation of itself. The encoding step is regarded as of foremost importance in genetic runs. The step is necessary to perform genetic crossover and mutation among individual chromosomes (solutions) to ensure population diversity.

The allocation algorithm starts by dividing the regeneration grid into uniformly labelled lots obtained from the 'mBPMOL' algorithm discussed in the previous section. The algorithm randomly looks for unassigned lots over the regeneration grid and saves the binary equivalent of each of the structure's top-left column and row position as shown in Fig. 4. The algorithm then starts with the assignment of each structure to one or more lots in an iterative manner until the minimum area required by the specific structure is achieved. 30 such individuals are generated to create the initial generation required for the genetic run to start with. Each individual is then passed through an objective function and through a selection process in order to be either retained or eliminated from the forthcoming runs. The encoding outcome for a section of procedural map is described in Fig. 4. The detailed GA methodology used for the overall genetic run is described in later sections.

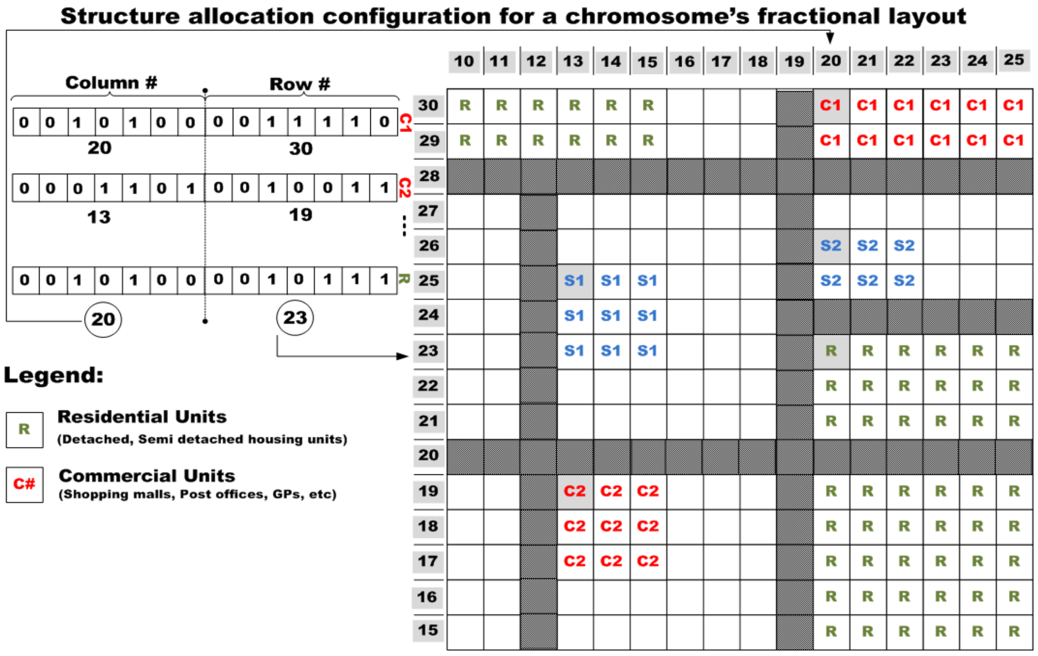


FIG. 4: Chromosomal assignment of service and commercial units to a uniformly distributed urban regeneration grid-plane

4.3.2 Fitness assessment of individual chromosomes for genetic selection with a cell suitability index

Selection is an operator that chooses a chromosome from the current generation's population for inclusion in the next generation's population. Before moving into the next generation's population, selected individuals may probabilistically undergo crossover and mutation. The resulting offspring then make into the next generation's population based on the outcome of an objective fitness function. The selection of an individual to be included or excluded from the next generation in order to undergo the process of crossover and mutation primarily depends upon the outcome of the fitness function associated with the main problem.

The scope of the current problem, that is, the initial search space comprise of the fitness evaluation of a set of allocated regeneration maps that are modified and manipulated using the concept of genetic evolution. The fitness evaluation was made based upon a number of socio-economic deprivation levels with the statistics taken from NeSS (2010) website. In order to materialize a robust location-allocation plan, a set of regeneration indices $d_R$were proposed for each of the four deprivation types considered in this study. These deprivation types include a wide range of socio-economic factors including crime, health, accessibility and employment. Deprivation is measured over a scale of 0 – 32, 482 where the lowest value indicates a high deprivation level. The selection of any of these factors remains outside the scope of this research and primarily depends upon the type of construction sought. Fig. 5 shows a sample grid distribution for regeneration R_a and neighbourhood areas N_a shown with solid and light-shaded cells respectively.

$$\delta_{mn}(r) = \frac{d_{N_{i,j}} \times D\left(d_{N_{i,j}} \cdot C_{a,b}\right)}{d_{R_{k,l}} \times D\left(d_{R_{k,l}} \cdot C_{a,b}\right)}$$

(5)

A suitability index $\delta_{\mathrm{mn}}(\mathrm{r})$ was calculated for all cells (lots) present over the regeneration grid as given in (5) where r is the type of regeneration index (crime, employment, etc) and $\mathrm{d_R}$ is the highest deprivation value for grid cell at k^{th} row and l^{th} column. $\mathrm{d_N}$ is the lowest NeSS (2010) based deprivation value out of the five N_a showing the highest deprivation area. D is the network (road) distance from current cell C_{ab}, for which the suitability index is calculated for, to either $\mathrm{d_R}$ and $\mathrm{d_N}$. The distance is measured from the cell C_{ab} to the "centre of mass of population" (COP) of each of the R_a/N_a shown as a grey cell in Fig. 5. The higher the $\delta_{mn}(r)$ value for any of the regeneration types, the fittest the cell would be to construct relevant service types to mitigate the regeneration-specific deprivation. On the other hand, a lower $\delta_{mn}(r)$ value cell placement would serve the neighbourhood deprivation better. An index value close to 1 will show a cell location holding an "equilibrium state" for both the neighbourhood and regeneration lots where the designers would be given an option to assign any type of service structure placement.

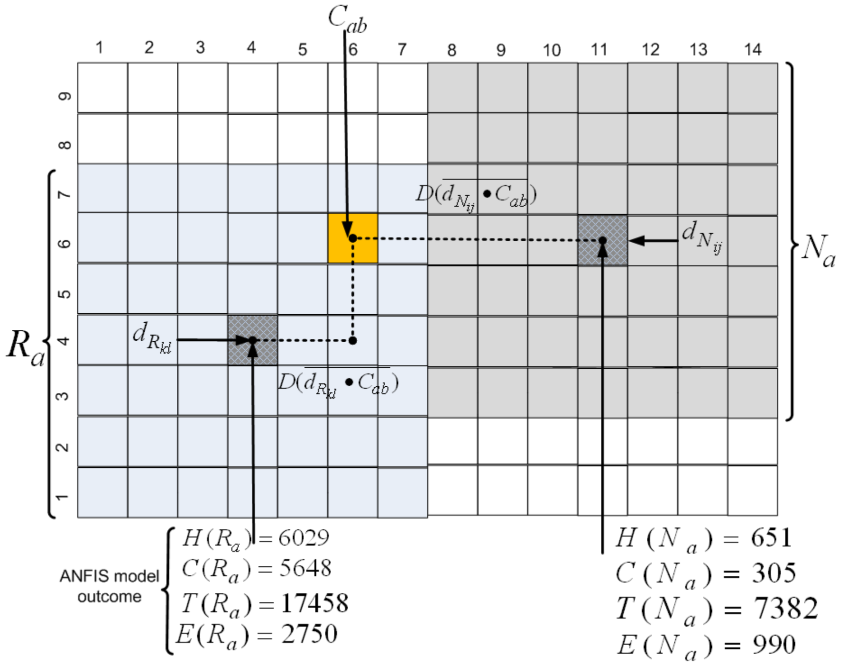


FIG 5: Calculation of a single cell index value $\delta_{4,4}(S)$ based upon National Statistics socio-economic deprivation values

Fig. 5 shows the calculation of a single cell lot regeneration index for ‘Services’ placement where the value can be calculated as follows:

$$\delta_{4,4}(S) = \frac{305\times5}{2750\times4} = 0.13 \tag{6}$$

Where 305 is the lowest value ($d_{N_{11,6}}$), which is that of crime deprivation, and 2750 is the lowest deprivation value ($d_{R_{4,4}}$), predicted by a neuro-fuzzy prediction model, which is that of the Employment deprivation $E(R_a)$. The distance is measured in number of grid-squares travelled from C_{ab} to each of the COP. The outcome value of 0.13 makes this the cell C_{ab} highly suitable to cater for $\mathrm{d_N}$. Crime deprivation is significantly higher (305) than the lowest deprivation present in R_a(5648) which is that of employment thereby making the cell ideal for structural placement for crime level minimization.

However, the entire grid plan containing the index values cannot directly be used for structure placement. In order to optimize the placement of various service and residential structures, a vacant urban plan must have a uniformly organized lot pre-assignment and an optimally connected street network. Generally, urban layouts consist of vastly unoccupied domains with planning areas extending to several square kilometres. As discussed in the earlier sections, manual creation of such a street network plan and lot layout is a time-intensive and tedious task. Furthermore, the procedural automation genre employing string rewriting algorithms has largely been used in stochastic domain only. This leads to the core novel implementation of this research, in addition to the mBPMOL module, of integrating procedural automation with genetic evolution to eliminate unsuitable layouts by means of the fitness assessment discussed above and retaining the best individuals for the actual run.

As the last step in phase 2, the fitness evaluation involves the assessment of the location-allocation of a range of public services along with a number of planned residential units using the suitability indices presented in (5) and (6) for cells. The concept is underpinned by the fact that adjacent built environment areas with highest level of socio-economic deprivation will, in general, propagate that effect to the adjacent/proximal regeneration lot. The objective then becomes to be the optimized placement of service structures along with the planned residential units in a pattern that also mitigates the deprivation of adjacent districts. This must be achieved in a way that does not compromise the core objective of accessibility to the planned residential units as well. The initial cell-level randomized building assignment algorithm is shown in Table 2.

TABLE 2: *Algorithmic data structure for cell-level randomised building assignment*

PUSH each service type s in priority to regeneration queue

S_{ab}	Priority Queue	Deprivation code
s_1	**Primary school**	**E/C**
s_2	**Shopping centre**	**E/H/C**
s_3	**Post offices**	**E/C**
s_4	**GP**	**H**
s_5	**Open space**	**H**
s_6	**Transport hubs**	**T/E**
s_7	**Residential**	**E/H/T/C**

E: Employment, C: Crime, H:Health, T: Transport and Accessibility

```
$T$: Threshold for regeneration lot assignment
For Each Regeneration Lot $C_{ab}$
  POP $service_{type} S_i = \min(d_N(S_i), d_R(S_i))$ from regeneration queue $S_{ab}$
    While Not End of Queue
      If $S_i$ not placed in immediate vicinity $(1.4\ km\ radius)$
        If occupied $C_{ab}$ not true and $\delta_{mn}(r) \leq T$
        Assign $C_{ab} = S_i$
        Occupied $C_{ab} = true$
        else
        continue
        End If
      else
        PUSH service type $s_i$ to regeneration queue $S'_{ab}$ end
        Continue
      End If
    End While
Move Next (Move to the next regeneration cell)
End For
```

4.3.3 Fitness function for genetic analysis of construction chromosomes

The core objective of GA based fitness function in this research remains to be the assessment of all the generated urban layouts similar to one generated by the algorithm given in Table 2 based on the underlying mBPMOL based procedural layout. The overall fitness for the current individual chromosome's fitness function $F(y_k)$ with p type(s) of planned services and q residential lot cells can be given as follows:

$$F(y_k) = maximize\left(\prod_{i=0}^{M}\left[\delta(r)_i \times \sum_{j=0}^{N} {}^{\omega_j}/_{D_i}\right]\right)$$

(7)

Where $0 < \omega \leq 1$

In (7) $\delta(r_i)$ is the most suitable "equilibrium state" value as defined in (5) with value closest to 1 selected from the four regeneration types, N is the total number of residential cell units selected for regeneration, M is the total number of planned public services, ω is the weight allotted to service k and D is the network distance of service i to residential lot j which is summed to obtain the total distance travelled from each residential cell to the specific public service S_i thereby giving a cumulative distance travelled by the residents to meet their everyday needs. Subsequently, the highest the cumulative distance to that service, the lowest the fitness output of the objective function $F(y_k)$ would be in the current genetic run. In order to test the fitness of any solution, the genetic system must be able to evaluate the specific layout in some way.

4.3.4 Case study-based evaluation of the highest fitness GA-based regeneration output

The test genetic run for the objective evaluation was carried for a planned case study of a regeneration village in Bilston, West Midlands, UK and its surrounding built environment. In order to provide a baseline comparison for the theoretical evaluation, the initial genetic run was transformed into a randomized search by increasing the mutation (bit flip-over) rate to 99% during subsequent generations. The solutions were evaluated according to the proposed fitness ranking already discussed in (7). Though the overall fitness for both the solution was almost similar with 24377 and 23341, case (a) started with a lowest fitness value of 7260 and took 360 generations to achieve a fitness convergence. Case (b) on the other hand obtained fitness convergence at generation 159. With the outcomes of the random search based genetic run as a baseline, the simulation was extended to a proper, controlled genetic run to evaluate the overall fitness of the entire system. The test genetic run for the objective case study evaluation was carried out as per the user requirement set shown in Table 3.

TABLE 3: *Urban regeneration grid layout parameters with equal weights assigned to all the service types*

Structure Type	Required	Units	Total Area
	Area (sq. meters)	Num of units	Area × num of units
Commercial Services ($\boldsymbol{C_R}$): (Supermarkets, grocery stores)	10000 - 40000	1	40000
Educational Services ($\boldsymbol{E_R}$):(Schools, community centres)	10000 - 20000	1	20000
Open space ($\boldsymbol{O_R}$): (Green space, parking lots, play areas)	10000 - 80000	1	80000
Health and Care Services ($\boldsymbol{H_R}$): (GPs, Surgeries)	200 – 400	1	400
Convenience Hubs ($\boldsymbol{P_R}$): (post offices, pay points, ATMs)	200 – 400	3	1200
Transport nodes ($\boldsymbol{T_R}$): (Bus stops, metro stations, train links)	10 – 30	1	30
Residential Unit ($\boldsymbol{R_R}$): (Detached, semi-detached)	400 – 100	300	60000

4.3.5 Selection of individuals based on specialist crossover/mutation operators

In order for GAs to efficiently explore the whole search space of construction solutions, it was required that generations were evolved with a significant level of variation. Performing a single-point crossover at a chromosome would have generated a layout with only a single relocated public service or residential lot resulting in an identical individual layout in the subsequent generation. Multi-point crossover, on the other hand, if carried out over the whole length of the chromosome, would have resulted in a probabilistic crossover of a single service thereby leaving a number of other structures without relocation over a range of individuals in subsequent generations. Since the aim was to explore the entire search space with location allocation of a wide-range and types of structures, simple single/multiple-point crossover mechanisms would not have efficiently provided the required generational diversity in the allocated space assigned to all the structures. In fact, a crossover at an improper bit would generate lot positions outside the actual regeneration area. This limitation required for a controlled crossover technique ensuring a proper allocation strategy for all the planned structures. To achieve this, specialist “multi-segment, single-point crossover” and “multi-segment, single-bit mutation” techniques were proposed as shown in Fig. 6.

Being a stochastic search method, it was difficult to formulate a convergence criterion in GA. As the fitness of a population remain static for a range of generations before finding a better individual the run was terminated once the 100th generation had executed. The parametric setup of the genetic run is shown in Table 4.

TABLE 4: Parameter setup details for Tier - 2 genetic optimization run for layout optimization

Parameter	**Run**
Crossover Frequency P_C	80%
Crossover Type	**Proposed:** Segmented-single point (controlled multi-point crossover)
Mutation FrequencyP_m	1%
Number of runs N_{pop}	100 generations (run terminated at 100th generation)
Individuals/generation I_{total}	30
Number of elite solutions N_{elite}	1 (single best individual selected per generation)

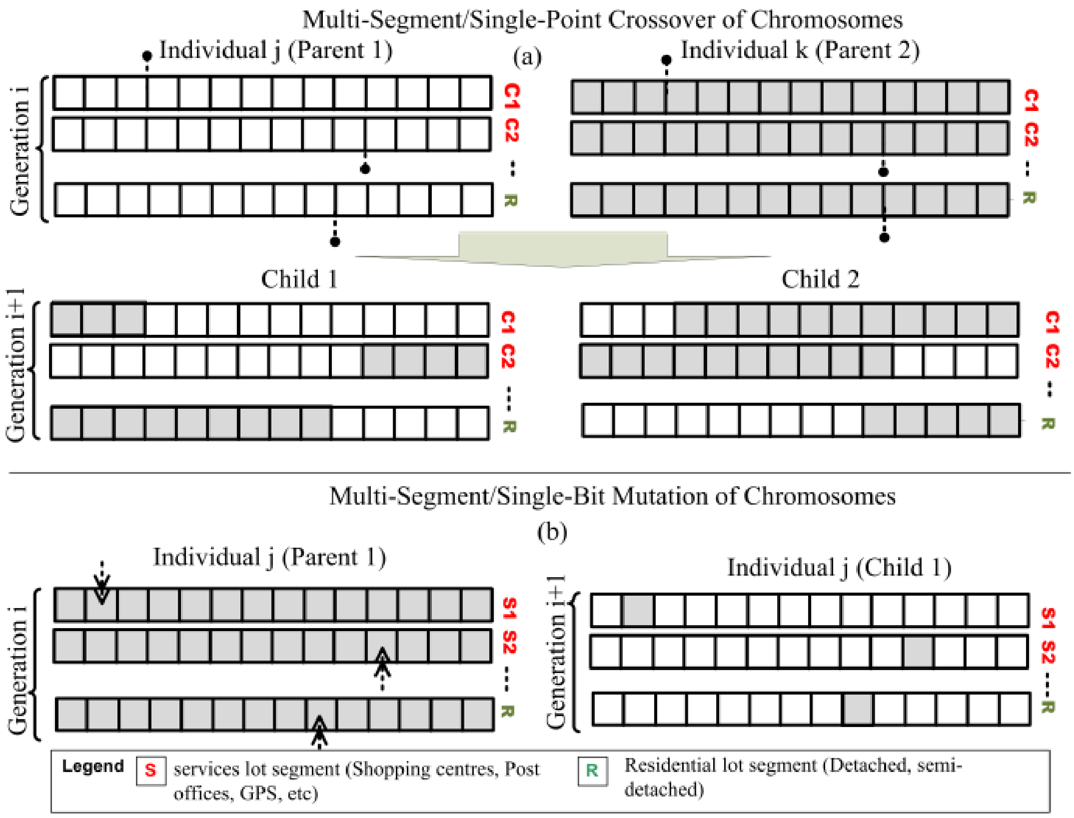


FIG 6: (a) Multi-segment single-point crossover of an array of public services (C1, C2 … S1, S2 … Sn) and residential unit placements (R) (b) Bit length mutation operator used for chromosome alteration with a probability of 0.01 (1% bit flipping rate)

4.4 Outcome of genetically encoded placement of procedural layouts

Fig. 7 shows the spread of socio-economic deprivation from the estimated ONS (2010) values to the modular outcomes of a neuro-fuzzy estimation model based predicted values within the regeneration areas. The propagation of deprivation due to neighbourhood areas is shown via elongated circles. The numeric values shown are calculated by ONS over a scale of 1 – 32482 with the lowest values showing highest deprivation levels.

Fig. 8 (a) shows the fittest layout obtained by the 20th generation in the run with a fitness value of 44497 whereas (b) shows the minimum fitness value with an individual for the same generation (k = 20) and a fitness value of 4155. A cross-comparison of the most optimal placement of various public services shown in (a) with Fig. 7 (a) – (d) can be made to evaluate the effectiveness of the simulator.

4.4.1 Layout optimization evaluation for "service access" deprivation minimization

The fittest solution shows a well-organized commercial area assignment over the lower-mid and lower-right region of the regeneration map which would likely contribute to the low "service access" deprivation that was evident from the ONS (2010) data in these districts (Fig. 7 - a). The solution with minimum fitness (4155), on the other hand, places roughly a quarter of the total number of commercial lots closer to the neighbouring high deprivation areas but still a major proportion of the assignment lies very far away from the access deprived regeneration district at the bottom left of the map which establishes the superiority of the objective fitness function for building placement.

4.4.2 Layout optimization evaluation for employment, health and crime deprivation minimization

For this specific case study, the socio-economic deprivation of employment, health and crime was dominant in areas closer to the town centre. The fittest solution showed a compact residential placement (dark colour lots) in closer vicinity to an educational district. The placement was robustly catered with supporting public services of convenience stores (Blue lots) and a centrally placed health node (Red lot). The services and residential areas were efficiently connected through transport nodes where open space lots were provided in the outer brim of the plan to prevent communal segregation within the regeneration plan.

Again, the minimum fitness solution in this case apparently offered a layout with highly segregated commercial and residential districts. In fact, the solution offered more of an unplanned outlook to the placement with no properly visible hierarchy in the placement of residential and public service structures.

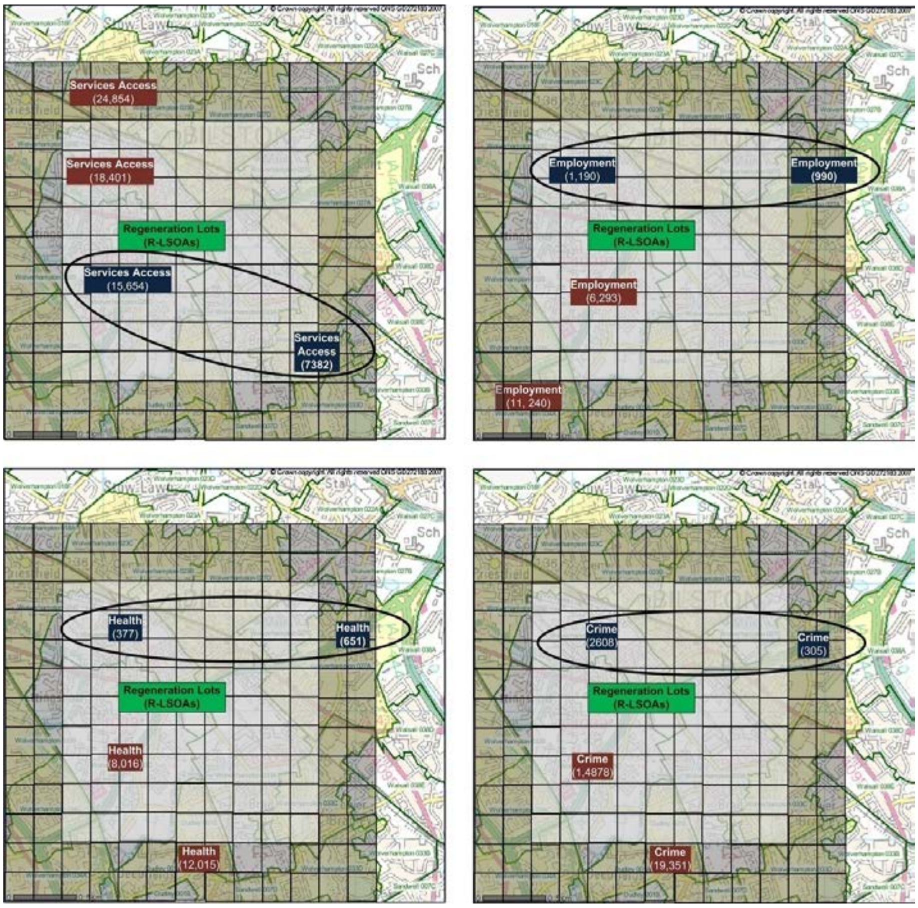


FIG 7: The underlying ANFIS based regeneration prediction values for (a) Service Accessibility, (b) Employment, (c) Health and (d) Crime

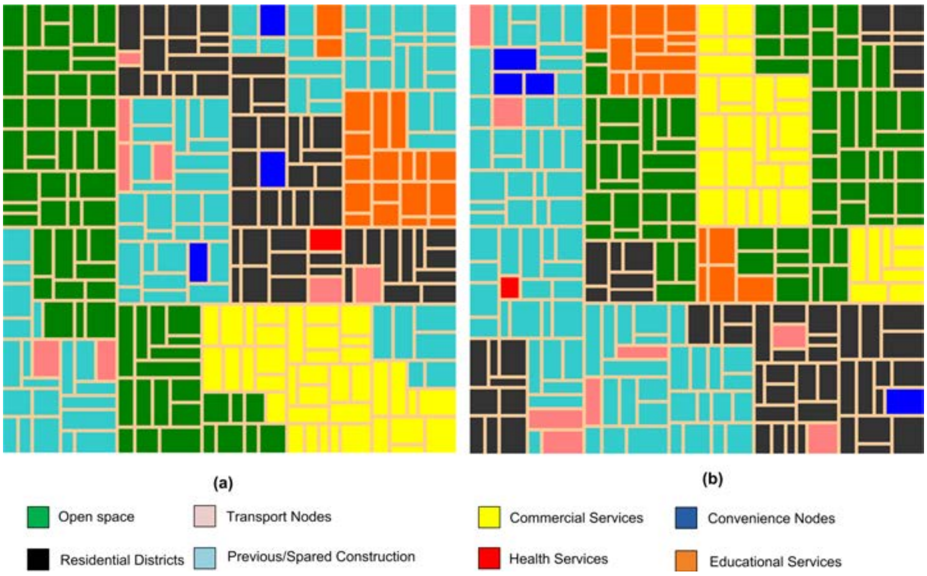


FIG 8: The best maximum fitness and minimum fitness solutions obtained in generation 20

4.4.3 X3D based Implementation of location-allocation optimization of GA outcome

The front-end of the toolkit was developed using Xj3D, a Java API for standard X3D based development for procedural mass modelling outcome visualization. The development of huge city layouts is a memory intensive process which was efficiently managed in Java. The availability and employment of a Java-based X3D explorer enabled users to navigate, pan, zoom or customize the output 3D mass models over the interface screen without ever downloading any add-on. Furthermore, JExcel API was used as a documentation API to record the entire evolutionary process onto excel spreadsheets. One such excel based sheet is shown in Fig. 8.

5. CONCLUSION AND FUTURE WORK

The work is a novel attempt to model AI-based structural placement and optimization as a substitute to stochastic procedural generation of urban mass models. The article proposed a novel methodology to automate the design layout generation for urban regeneration and planning purposes based over a set of underlying deprivation attributes and AI techniques.

The algorithm used to automate the modelling of massive built environments utilized the underlying concept of cellular division previously presented as ‘mBPMOL’ systems. The very notion behind this layout automation was to provide a base framework to encode the allocated lot positions into a genetic chromosome in order to initiate the evolution of urban form. The outcome successfully generated a family of individual chromosomes (solutions) containing variable layout choices within an urban regeneration layout. The individuals were evaluated using a set of regeneration indices over a basic distance criterion of lot distance to neighbourhood deprivation. The outcome, obtained over a set of 100 generations with each containing 30 chromosomal construction layout solutions generated efficient design outcomes based upon an access maximization objective fitness function. The outcome was evaluated over a real-world urban regeneration case study and cross-validated with a model based upon NeSS deprivation data.

The project’s outcome, though holistic on its own, can still be extended over a number of aspects. The data used in this work for fitness function evaluation was taken from NeSS (2010) databases. The impact of neighbourhood deprivation on regeneration districts was predicted using a neuro-fuzzy model which can be extended to accommodate a wider range of variables such as pollution, energy efficiency, etc. Furthermore, the concept can be used to assess and analyze the impact of natural disasters such as forest fires, floods and earth quakes over the social and economic sustainability of urban built environments. Finally, the theoretical baseline of the work can still benefit from a multi-objective approach catering a number of conflicting criteria such as placement of a hospital closer to a busy traffic hub in addition to the placement of industrial units for employment in proximity of residential districts.

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