Achieving Residential Connectivity and Density Goals with Computer Generated Plans in a Greenfields Area

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Received 7 July 2011; in revised form 22 January 2013; published online 31 January 2014

Abstract

An algorithm has been developed to generate, without external intervention, a road and land use plan for a regular or irregular site. It starts from an 'embryo' and grows a plan rather than trying to modify an initial solution. The basic modules are universal building blocks which change and adapt in a guided search with random selection of branching points followed by operations to add links or make connections. Deletion operators guide development by removing branches which do not improve the outcome. A hypothetical application, maximizing combined everyone-to-everyone connectivity and dwelling density, has evolved a highly interconnected street plan.

However no step is specific to the example; the operators will grow a road and land use network under various specifications and constraints guided by an objective function. Making the process applicable to an actual development might require more constraints and certainly an enlarged objective function. Cost and other goals can be included so long as each goal is in some way functionally related to every change in the plan made by the search procedure.

1. Introduction

The goal of this research has been to develop a computable model using artificial intelligence for urban layout optimization. Although computers do not possess the cognitive ability to perform planning tasks in the way that humans do, they are more capable of doing a thorough search in the design space so that the likelihood of finding nearly optimal solutions is much higher.

The developed algorithm can be initiated for any vacant area and allowed to develop a plan based on specified goals. It guides an iterative search process and the resulting plan may exhibit emergent properties (cf. Doyle et al, 2013). In the example used in this study, the property of 'ringness' emerges, as discussed later.

The presentation in this paper has four objectives:

1. To present a new model for planning a street system and residences in a vacant area with or without existing obstructions or reservations;
2. To apply the algorithm to an abstract example and to show the versatility of the algorithm;
3. To present and illustrate the elements of the model, implementation of an objective function and the way in which the algorithm develops a plan;
4. To compare objective values of the plan computed for the example with grid plans for the same example space and the pedestrian route directness (PRD) value with published values.

The purpose is to develop a model capable of generating a network for a new site, not to model the intricacies of an existing network nor to indicate how a precinct might evolve under real world influences (cf. Batty, 2010). Although this study grew out of an investigation of the impact of a 2007 extension to the Perth, Western Australia, rail network, that was merely the impetus and none of the features of the particular area has influenced the development of the model.

1.1 The hypothetical example: a suburban residential development

The developed algorithm can be used for a variety of situations but the main application reported here is to an abstract suburban space. Modelling the layout of a suburban residential development involves the creation of what has come to be regarded by some as a ‘placeless nowhere’ (Phelps, 2010). However Phelps comments that ‘...it should be no surprise that such a seemingly contradictory and imperfect urban form as suburbia can, and, indeed, does compose an integral part of contemporary capitalism.’

Lovejoy et al (2010) note that a suburb often lacks the grid-like street pattern, mix of residential and commercial land uses and distinct centres usually associated with ‘traditional’ neighborhoods. Nevertheless, their rigorous quantitative assessment leads to the conclusion that ‘...some of the main differences between suburban and traditional neighborhood designs do not make much of a difference for how satisfied residents are with their neighborhoods, in either neighborhood type.’

When comparing suburban neighborhoods in Houston, Rogers et al (2009) found that ‘...residents in ecologically designed neighborhoods have an enhanced sense of community, at

least in terms of supportive acts of neighboring and neighborhood attachment and social ties...’ and that ‘Ecosystem design uses public spaces, especially those outdoor spaces such as parks and pedestrian walkways, to promote community identity, social contact and interaction, which enhances the sense of community in the neighborhood.’

A particular point that is carried into the modelling example is that a residential suburb need not have the centralising character of a village or town (Lovejoy et al, 2010). However this is not inherent in the algorithm and a modified objective function could result in the generation of a village layout focused on a central area. The algorithm does not itself insert the public or commercial sites and spaces but is designed so that after these have been specified the model will build the residential precinct around them.

The first modelling objective of the hypothetical example is to maximise social contact and interaction (Rogers et al, 2009) the ‘key difference from conventional practice’ being that ‘the street system is highly interconnected, and is aimed at reducing local travel distances’ (W.A. Planning Commission, 2009). Such statements were taken to be applicable to the example, reflecting a performance objective in the sense of Capello (2000). The specific measure of what makes a street system highly interconnected is discussed in Section 4. The second modelling objective is to maximize housing density subject to whatever separation requirements are imposed (Section 3.2).

It is emphasised that this is an exercise in modelling method for undeveloped sites. Although an entry point to a rail station is considered, the model is not about service to an existing population. For people already living near the railway mentioned above, service and personal choices have been studied by Olaru et al (2011). Related work to delineate park-and-ride market areas has been reported by Farhan and Murray (2005). Returning to optimization, a model to delineate emergency shelter service areas has been developed by Li et al (2008) but again this is for an existing population. The only ‘service’ considered in this example is potential access to others in the modelled development area and the interaction is purely hypothetical.

2. Selection of the modelling method

Modelling methods that have been used in the urban planning field include agent based (O’Sullivan and Haklay, 2000; Gero and Sarkar, 2005; Jordan et al, 2012) and cellular automata (Barredo et al, 2003; Fang et al, 2005; Waddell, 2002; He et al, 2008; Santé et al, 2010) as well as combinations of the two (Batty, 2005; Torrens and Benenson, 2005). Other combined models of urban growth processes include cellular automata (CA) with fuzzy functions (Vancheri et al, 2008) and CA with logistic functions (Poelmans and Van Rompaey, 2010). Mathematical programming has been used effectively (e.g. Janssen et al, 2008) but has not been widely applied. Genetic algorithm (e.g. Feng and Lin, 1999) is an appropriate method of evolutionary modelling and was tested in this study but development of a satisfactory crossover operation was a serious difficulty and an alternative procedure was adopted, as explained later. The model used by Ning et al (2011) seeks to optimize layout in an empty space, as in this study, but is restricted to allocating buildings in a construction site. Their algorithm is specific to the particular problem and includes an element of fuzzy assessment.

The use of cellular automata shares with the method presented here the characteristic of being a bottom-up approach, in which the macro-level system behaviour is determined by micro-level interaction among cells (Wolfram, 1984; Dietzel and Clarke, 2006). Agent based modelling is also a bottom-up method described as ‘a self-contained problem-solving system capable of autonomous, reactive, proactive, social behavior’ (Wooldridge and Jennings, 1999). The modelling platform for this study is an agent based traffic microsimulation but only one component of traffic assignment is used.

2.1 The development platform

The Aimsun microsimulation was chosen as the development platform because:

- It has built-in modelling entities needed in this research, particularly roads, intersections and traffic centroids. Most of these entities are graphically vector-based (as opposed to pixel-based) so that they can be manipulated easily by changing parameters.
- The shortest path algorithm calculates street step distance between every pair of dwellings.
- Aimsun is written in C++, which ensures its computational efficiency.

- Aimsun SDK (software development kit) offers access to its internal classes, which can be either directly called or used to create new classes.

The application modules are all programmed in C++ through Aimsun SDK for efficient computation. The topological relationships of the objects (roads, houses, etc.) are defined to limit the search space to feasible arrangements. For example, each house must be connected to at least one road and each road must be connected to at least another road and must have access to an entry point through the network.

Figure 1 A T-junction modelled as a node point using the Aimsun development platform

A key element is a node where two or more road sections are joined. A series of sections can represent a continuous road, the nodes joining them being artefacts rather than real junctions. Other nodes do represent junctions, as in Figure 1 showing a T-junction in which six turns are defined. In this application the three sections are treated as meeting at the Node Point but in reality a junction occupies space and its geometry would need to be properly designed when a plan is implemented.

3. Modelling elements and steps

The basic building block comprises a segment of road with ten dwelling centroids (Figure 2a). Growth starts from this universal module acting as the embryo at the site entry, ensuring that the whole network is connected to the external road system. If there are multiple entries there is an embryo at each one.

(a) (b)
Figure 2 The basic module (a) and a road extension with three dwellings replacing one (b)

The dwelling on the right of Figure 2b is replaced by a road section and three dwellings are added at its end. The process continues in semi-random steps leading to space filling plans as in Figure 3.

Growth of either type in Figure 3 (switching off the 45° option gives orthogonal growth) generates plans which fill a regular or irregular space and may appear reasonable. However such a plan is a tree structure which has poor internal connectivity, even though it may give good access to a particular facility such as a train station.

The key point is that the modules are universal building blocks that can change according to the local context. They adapt as the plan evolves.

Figure 3 Segments of evolved plans with (a) angled or (b) purely orthogonal growth

3.1 Operators

The functions required to build the network fall into four groups:

Adding road sections or dwelling centroids (3 operators). One example is in Figure 2b – an added road section with added dwellings. Any dwelling centroid is a potential branching point; the branch eliminates the dwelling and may eliminate others to avoid violating the separation constraints.

Linking two nearby dwelling centroids or a centroid to a nearby road section (2 operators). To avoid forming small dead loops there is a minimum network distance between the elements to be linked. One possible example of a linking process is shown in Figure 4.

Figure 4 Sequence of steps in forming a new circuit by linking

Deletion of a centroid or road section and removal of any branches disconnected in consequence (2 operators).

Verification to check for violation of constraints (6 operators).

3.2 Dimension constraints: hypothetical example

Dimension constraints in the example are for detached housing:

Space between dwellings: 14 m.

Road width (3.5 m. per lane): 7 m.

Setback, road to building block: 4.5 m.

Setback line to rear boundary: 21 m.

Housing to development boundary, internal reservation or natural feature: 7 m.

Figure 5 (a) Separation and minimum block size (b) Size variations with non-orthogonality

These give a block of 294 m² (Figure 5a) and 25 dwellings per hectare. The block may be larger on a bend as in Figure 5b, reducing potential dwellings to about 21 per hectare.

Road segments may meet at 180° , making a straight road as in Figure 2b, or at 45° or 90° . When implementing a plan 45° angles would be smoothed to become curves. In an orthogonal model, road segments can only meet at 180° or 90° (Figures 3b and 4).

3.3 Random generation of a 'tree' with random linking

To indicate the effect of growth operators alone, Figure 6 shows the result of filling a 25 hectare example area from one entry point with the adding and linking operators only. All (randomly) attempted feasible applications are executed. Without cutting, this model has no reversibility or self-correcting capability but simply tests the result of adding road sections.

Figure 6. Randomly generated layout using branching and linking operators

4. Quasi-optimal development

Deletion operators and an objective function are introduced to control and fashion growth but there is no guarantee of achieving the highest possible objective value. Most steps increase the value but the outcome differs at each model run. The objective function in the example incorporates internal connectivity and residential density goals.

4.1 An internal connectivity goal for the example

The internal connectivity goal – specified in relation to previous research in order to make the example relevant and indicative of the algorithm's potential – is a particular type of centrality, a concept which had early applications to communication and influence among groups of people (Freeman, 1979). When centrality is applied to networks the focus may shift from central nodes to the distribution of centrality values through all nodes. Centrality "is treated like a shared

resource of the network ‘community’ – like wealth in nations – rather than the unique property of the excellent" (Porta et al, 2008). However the measurement of centrality can be approached in various ways each with its own implications (Porta et al, 2006).

The example is concerned with a street network facilitating social contact, based on the view that ‘human societies use space as a key and necessary resource in organizing themselves’ (Bafna, 2003). Instead of centrality being a relationship between a single node and others (Jiang and Claramunt, 2004) it is generalized to cover the centrality of each residence in relation to the others.

4.1.1 Measuring internal connectivity

Major contributions to connectivity concepts are associated with space syntax, the way in which space is configured (Hillier and Hanson, 1984). Relations are measured between elements located in geographical space but these relationships are topological, not Euclidean measures of association (Batty, 2004). Space syntax treats the distance between nodes (streets) as the number of intervening edges (intersections) along the shortest path, using the number of intervening ‘steps’, whatever the lengths of those steps (Porta et al, 2006). Space syntax implies that better connectivity is related to fewer turns in the routes between houses rather than with the actual shortness of distance between them.

Associated with space syntax is intelligibility, described by Blanchard et al (2008) as a part-whole relationship between local and global properties of the spaces of motion. Bafna (2003) says that the intelligibility of a configured space is the property that allows a situated or immersed observer to understand the space in a way enabling that person to find his or her way around in it. Intelligibility is defined in terms of the correlation between connectivity as in space syntax and integration, the latter representing the average depth of the spatial unit from all other units, being affected by the entire spatial configuration. Bafna (2003) contrasts a grid structure, where it is difficult for people to orient themselves, with streets in a market town providing cues which bring even a disoriented visitor to the main streets. Environments providing cognitive cues for both local and global properties of space – so that the two are correlated – will ‘feel’

intelligible.

Batty (2004) has shown that the topological measures of space syntax can be augmented with measures based on Euclidean distance, each segment between nodes having coordinates from which straight line distances can be computed. However the correlations based on shortest paths and the space syntax measures of accessibility in the benchmark village of Gassin are low. Omitting any account of the number of turns makes distance by the shortest path very different from the topological measures.

Experimental work on people navigating from one location to another has been reported in the psychology literature. Bailenson et al (2000) noted that observed asymmetries in route selection conflict with choice of the shortest route. One experiment indicated that subjects prefer a straight initial portion, regardless of how circuitous is the rest of the route. In another experiment using maps, subjects preferred straight paths over alternatives with turns, a result consistent with space syntax. As a comment on asymmetry, traffic assignment models based on stochastic user equilibrium (e.g. Bekhor et al, 2008) recognise that actually chosen routes are distributed around the shortest path, which allows for a different route on a return trip.

The work of Wiener et al (2004), using virtual environments, suggests a tendency to focus on local landmarks. Subjects did not perceive or report a conflict when global landmarks were rotated while local landmarks were kept stable. Yang et al (2011) found that participants in experiments preferred the route whose initial direction was toward the final destination, with turns being less influential. However they too used maps for their experiments.

Hölscher et al (2011) asked participants familiar with an area (downtown Freiburg) to plan the route they would follow to a particular destination. But when asked to walk to that destination, all twelve participants deviated from the planned route, making it considerably shorter by including more turns. More complex tasks with 24 participants and explicit map based planning gave a similar result: the routes actually chosen when walking were considerably shorter than the planned routes and had more turns. The authors conclude that directions given to a stranger are simple and easily remembered whereas one's own route is fairly direct, usually

including more turns than the easily described route.

While recognising the significance of space syntax measures, we have chosen a connectivity measure based on the sum of the step lengths between pairs of residences on two grounds. The first is the evidence suggesting that the routes actually taken by residents between points, as distinct from planned routes, are close to the shortest paths, regardless of turns. The second is that the modelled example is for a suburban area with none of the central character of the village of Gassin or a city centre. This is also the basis of the decision not to include an intelligibility measure: the example is intentionally modelled in the imperfect suburban form noted by Phelps (2010) without a distinct centre (Lovejoy et al, 2010) and is designed for residents who can find their way around, not for disoriented visitors (Bafna, 2003).

Thus the example uses the ratio of direct Euclidean distance to the sum of step lengths on the shortest path between every pair of dwellings (Figure 7) averaged over all pairs, being equivalent to connectivity as used by previous authors (Hess, 1997; Randall and Baetz, 2001; Dill, 2004). The goal of maximising this measure, ‘straightness centrality’ (Crucitti et al, 2006; Wang et al, 2011) implies that interactions are strongest along shortest paths.

Figure 7 Contribution to straightness centrality by one pair of dwellings
(ratio of direct ‘arrow’ distance to shortest road distance – shaded)

4.2 Specification of the full objective function for the example

If D_e is Euclidean (straight line) distance between centroids, D_n the shortest network path between them and n the number of centroids, excluding those in the same cul-de-sac, then

straightness centrality is defined here as:

$$C_{avg} = \frac{\bar{a} \frac{D_e}{D_n}}{n(n-1)/2} \quad (1)$$

As the distance from centroid r to centroid s is the same as from s to r , there are only $n(n-1)/2$ separate paths. Any pair of centroids that belongs to the same cul-de-sac give a D_e/D_n ratio of one which is not included in the average centrality. Although this deliberate omission imposes a downward bias on C_{avg} , it limits the number and length of cul-de-sacs. For a single pair of centroids, the numerator of the straightness centrality formula is the reciprocal of the pedestrian route directness ratio (Hess, 1997; Randall & Baetz, 2001; Dill, 2004).

The second goal in the example is to maximize dwellings. One way of combining goals is to form a weighted sum of average dwelling centrality C_{avg} and number of dwellings H . However, possibly because the appropriate weights were not found, this objective gave results that were inferior to the product of the two goals – which requires no weighting. Consequently the objective function is a product:

$$X = C_{avg} * H \quad (2)$$

Only one house in any cul-de-sac is included in n (Equation 1) so that n does not cancel with H .

Although station access is not an added goal, pedestrian route directness (PRD) to the station is an important measure (Kuby et al, 2004) and is compared with previous studies (Section 6.2). No regular forms are imposed on plans, which may run counter to some aspects of new urbanism (cf. Brown and Cropper, 2001; Lund, 2003; Cozens and Hillier, 2008).

4.3 The search for an optimizing procedure

Finding the best optimizing algorithm for the task has been difficult but revealing. Porter et al (2008) comment: ‘The first extreme is to gain deep insight into the structure of the problem, and craft highly specialized algorithms based on this insight. The other extreme is to identify relatively shallow heuristics, and hope that these, coupled with the ever increasing computing power, are sufficient.’ This study began at their second extreme, using available search

heuristics, but experience showed that the algorithm developed for the specific problem is more effective as well as being more efficient.

Simulated annealing (SA) – somewhat like genetic algorithm (GA) with an active modelling population of one – was adopted after GA was abandoned. SA changes the single existing plan but may revert to a previous plan. With random experimentation SA will accept many inferior changes in the early stages but becomes more selective until only clear improvements are adopted (Mahlke et al, 2007). Watts et al (2009) note the use of SA in spatial conservation planning.

Another strong performer, closely related to SA, is Michalewicz and Fogel's (2004) stochastic hill-climber (SHC). The SHC probability of accepting a change varies with objective function improvement. Either SA or SHC is a 'relatively shallow heuristic', in the sense of Porter et al (2008), which had to be adapted to the network layout problem. The operators guided by the objective function were able to grow, remodel and repair to achieve progressively superior outcomes. However the SA or SHC eventually became redundant because the rules and operations embodied in the modelling algorithm were themselves able to make improving steps efficiently while ensuring the degree of randomness necessary for a search. Although the resulting procedure amounts to crafting a highly specialized algorithm in the sense of Porter et al (2008), it is not specialized to the example but to the class of planning problems.

4.4 Application to the hypothetical example

Each potential extension to the network is assessed by the objective function which requires a separate calculation for every pair of dwellings. For an average of about 350 dwellings this means more than 60,000 calculations at each application of a linking or cutting operator. There are typically 100 computation cycles with at least 50 operations for which the objective is evaluated (giving almost 300 million shortest path determinations, and an equal number of relatively simple Euclidean distance calculations, between dwelling pairs).

4.4.1 Operator sequence and acceptance

The Table 1 sequence was used to generate the results in Figures 8 and 11. Operators are applied

in sequence but an application to a randomly picked target may not meet constraints so that the success rate can be low. Therefore the program tries each operator at random locations for multiple times, as indicated in the last column of Table 1.

Table 1. Operator sequence leading to Figure 8

Sequence No.	Functional Group	Operator	Number of Times Executed
1	Deletion	Delete centroid with lowest centrality	10
2	Deletion	Cut	10
3	Adding	Bud_Dwellings	300
4	Adding	Bud_a_Module	100
5	Linking	Link_Dwellings	20
6	Linking	Link_Road_to_Dwelling	20

Cutting (Sequence 2, Table 1) removes bad structures, a first step in remodelling, but there is no payoff in objective function $C_{avg} * H$ until dwellings refill the cleared space. In a Bud_a_Module operation (as in Figure 2b) a house is sacrificed to generate up to 5 houses, a net yield from 0 to 4: an operation with a net yield of 1 or more is accepted. Bud_Dwellings and Linking operations are accepted if feasible.

5. Quasi-optimal results

An objective function with cutting changes the plan substantially from what can be developed by growth operators alone. Sub-section 5.1 deals with the main example, covering the same square area as in Figure 6, and 5.2 illustrates algorithm versatility.

5.1 Example: planning an unobstructed square area

Figure 8 is similar to Figure 6 but with applications of the objective function and cutting, followed by reconstruction, as indicated in Table 1.

Figure 8. Quasi-optimal layout obtained by randomly targeted branching and linking and cutting (computation step 96)

Computations leading to Figure 8 are guided by the composite objective function which initially increases steadily (Figure 9). However in this run the cutting and redevelopment leads initially to violent fluctuations in straightness centrality (Figure 10).

Figure 9. Successive values of the composite objective function in the evolution of Figure 8

Centrality (Equation 1) reached 0.650, with 441 dwellings. In contrast, the Figure 6 plan for the same area, generated without an objective or cutting, has average centrality of 0.605 and 383 dwellings. The plan in Figure 8 demonstrates an outcome of the quasi-optimal process and is the culmination of the sequence of steps illustrated in Figure 11.

Figure 10. Successive values of straightness centrality in the evolution of Figure 8.

To show the severity of cutting, Figure 11 presents the plan at step 6 and then at intervals thereafter. The algorithm cut the structure to the north-east at step 20, allowing development of new structure by step 30. Even that new structure suffered several cuts and redevelopment in later steps. An example of efficient cutting and redevelopment is provided by the road section which is too close to the south-western boundary to allow dwellings on its southern side (plans 6 through 20). At step 25 it has been deleted and by step 30 it has been replaced.

Figure 11. Cutting and re-growth in plans leading to Figure 8 [clean versions to be prepared]

5.2 Plan generation for an irregular area with reserved spaces

To enhance the sense of community (Rogers et al, 2009), outdoor spaces may be specified and the model will build the residential precinct around them. Figure 12 shows the model developing a curvilinear space embracing three reserved areas. As the plan evolved from five entries, the five separate road networks linked and became continuous.

Figure 12(a) Incomplete plan with five entries and three irregular reservations

Figure 12(a) shows one network developing from the two entries in the Eastern part and another developing from the three in the West, with a gap between. Figure 12(b) shows how the model closed this gap as computation progressed.

Figure 12(b) Almost completed plan

The artist's representation in Figure 13(a) of an area adjoining the small reservation in the south-west of the plan in Figure 12 indicates appropriate amenity in terms of houses and landscape.

Figure 13. Artist's representation (a) of the street layout in (b) portion of Figure 12 plan

The main point is the model's capacity to cope with variable topography. Also this example shows that growth from separate entry points is made possible by the linked circumferential roads. Any precinct is likely to have multiple entries and model application requires a prior link between them. It could be a hypothetical link to be discarded partially or entirely when the plan is completed.

6. Evaluation of hypothetical model

Model improvement is continuing but Figure 14 shows a result which is better than Figure 8 and has been used for evaluation comparisons even though a little inferior to subsequent results. The final lot layout, to be generated by some type of computer aided design (CAD) software, would show a normal arrangement of block boundaries and street frontages, as in Figures 5 and 13a. The 495 dwellings in the 25 hectare area give a density of 19.8 dwellings per hectare.

Figure 14. Street and house layout for internally accessible development evolved by computer algorithm (before inserting block boundaries)

6.1 Comparison with grid networks

Using the same dimensions and constraints as for Figure 14, a number of grid layouts have been manually developed for comparison. Appendix 1 shows the three best of these grid layouts which are compared in Table 2 with the algorithmic model of Figure 14.

The Figure 14 layout achieves the highest dwelling density (Table 2) partly because of cul-de-sacs even though these have been partially suppressed by the objective formulation. However dwelling density has not been at the expense of interconnectedness which is almost as good as in the best of the grid layouts. In contrast, the grids achieve their centrality values at a high cost in dwelling density. There is a degree of irony in the fact that the model which generated Figure 14

was developed to achieve everyone-to-everyone centrality but its success is in housing density with little sacrifice in centrality.

Table 2. Comparison of grid networks with the model developed by the algorithm

Model	Number of Dwellings	Everyone-to-Everyone Centrality (Eqn 1)	Objective Value (Eqn 2)
Grid model 1	388	0.574	223
Grid model 2	374	0.656	245
Grid model 3	346	0.690	239
Figure 14	495	0.638	316

The algorithm achieves comparable accessibility to the grid layouts by evolving a high degree of ‘ringness’ (Hillier and Hanson, 1984), defined by Erath et al (2009) as the ratio of the total length of arterials on rings to the total length of arterials. Here the ratio refers to all roads; the higher it is the shorter are the routes between pairs of dwellings. Ringness is not a goal but emerges as a result of the search for short routes. Figure 15 shows a low proportion of shared roads and thus a low level of ringness. In contrast the computed plan in Figure 14 shows 12 circuits with many shared road links giving a high degree of ringness and interconnectedness. Roads in circuits amount to 78% of total road length.

Figure 15. Three road circuits showing shared links in bold

6.2 Comparison of pedestrian route directness

Pedestrian route directness (PRD) deals with access to significant locations. The PRD ratio is the reciprocal of straightness centrality but is averaged over the ratios of road distance to direct distance from each dwelling to the destination. Many PRD measures are to central points, such as schools, whereas ours is to the entry point (notionally a train station).

Table 3 shows PRD calculated by various methods in six previous studies. Some use large samples of actual trips while others are calculated from selected points. Although not strictly comparable, they all measure essentially the same thing. The lowest (most favourable) value is 1.2 for access to the central area of Wallingford a neighbourhood with a grid street pattern and small blocks (Hess, 1997). As Bejleri et al (2009) note, ‘...early road networks were of a gridiron pattern and thus have higher connectivity.’

Table 3. Comparison with reported street based pedestrian route directness (PRD)

Source	Destination	Study Location	Case	PRD ^a
Hess (1997)	Centre	Seattle, Washington	Wallingford	1.2
			Crossroads	1.7
Randall and Baetz (2001)	School	Hamilton, Ontario	Base case	1.70
			Improved	1.37
Timperio et al (2006)	School	Melbourne, Victoria	Average	1.6
Chin et al (2008)	School	Perth suburbs, W. Australia	Conventional	1.63 to 1.93
			Traditional	1.44 to 1.60
Yi (2008)	Park	Houston Heights, Texas	Average	1.57
	School		Average	1.36
Bejleri et al (2009)	School	Tampa, Florida:	Hillsborough County	1.9
			Pasco County	2.0
Figure 14	Station	(hypothetical)		1.32

^aPedestrian Route Directness ratio, excluding off-street pedestrian networks

Although the hypothetical model does not have a PRD goal, Table 3 indicates that its interconnectedness ensures good access from dwellings to train station similar to the accessibility in many existing residential areas.

6.3 Modelling issues in the examples

One issue is that near the optimum there are only small increases in objective value but changes in layout may be substantial. Work is continuing to refine the algorithm’s performance in these later stages.

Another issue is the algorithm’s acceptance of apparently unproductive features. The irregularity of circuits is an effect of random target selection but there is no payoff from straightening them. A small modification may even lose a dwelling without an offsetting

increase in centrality. A further anomaly is acceptance of a few long cul-de-sacs which add dwellings even though average route distance to other dwellings is high. Joining cul-de-sacs to create a circuit will lose dwellings which may not be offset by increased centrality.

With respect to the evolutionary method, a further potential optimization enhancement would be to use genetic algorithm to determine the best operator sequence and other parameters.

7. Actual application: generality of the algorithm

The remaining issue is the way the model would work in an actual planning task and the added criteria that would come into play if it is to be used to design a project. For instance there are vacant sites where the 25 hectare example could be implemented but this would entail laying out services in addition to roads, particularly water supply, sewer lines and storm-water drainage; additionally the topography and soil conditions might put constraints on the road network. The least acceptable approach would be to take the plan as a given and expect project engineers to adapt the services to it. This would only be tolerable if nothing in the implementation invalidated any part or aspect of the modelled plan.

The more adequate approach is to incorporate all significant issues in the modelling procedure. Topography or soil conditions could be treated as constraints – like the reservations in the second example – but it would be more realistic to vary costs according to conditions. A developer or planning agency seeking to minimize infrastructure costs would need these to be included in the objective function. Any goal can be included so long as the effects of each network modification in the iterative search can be properly counted. For instance drainage costs would be functionally related to road costs and other services would be functionally related to dwellings or roads. However a service that deviates, possibly a water or sewer main, may have to be treated as a separate engineering task when the plan is implemented.

Changing or enlarging the objective function poses no serious problems. Costs might simply be specified as cost per metre of road plus added costs for intersections and culverts. Soil conditions could be mapped and road cost varied accordingly. However there must be at least one benefit goal: a simple objective function would be to maximize the sum of the money value

of dwellings less the developer's costs. A more complex planner's objective would be to maximise something like the composite connectivity and dwellings goal used in the example, weighted to give it an arbitrary money value, less development costs. Going further, the whole character of the model application could be changed by using as the main structural goal pedestrian route directness or a space syntax measure of accessibility. These are countable and functionally related to the road layout, though not necessarily easy to calculate repetitively.

8. Conclusions

The outcome of this study is a general algorithmic model to create new layout designs. There is something of a 'chicken and egg' relationship between the development of the general algorithm and the particular application. It is unlikely that the final algorithm could have been developed in the abstract; early ideas and concepts did not lead directly to a model for evolving residential plans. Instead the successful algorithm was painstakingly developed in step by step work applied to a hypothetical example.

Thus the concentrated work has gone into developing a computer model that optimizes residential layout for a hypothetical site in terms of internal connectivity and dwelling density. The resulting model is capable of developing a plan, from any number of entry points, to fit into almost any space which may be irregular and contain reserved areas. The plan generated for the example has been compared with three grid layouts for the same hypothetical area using the same constraints. The test indicates high performance in terms of the set goals, 27% more dwellings, 94% as much everyone-to-everyone connectivity and 31% higher composite objective function. Other goals would require other tests.

However the real outcome is that a versatile general algorithm has been created. The difficult part has been to make the operators and the modelling steps work together so that structures are built, evaluated and repeatedly modified until a high valued plan is achieved. Key features are the adding, linking and deletion operators guided by an objective function. At the heart of these operations are the basic modules: as the plan develops, these universal building blocks change and adapt according to the local context. Another core feature is that the algorithm grows a plan

rather than trying to modify a complete solution from the beginning. A model starts from an 'embryo' and grows in steps.

None of the operations is case specific; they will grow a road and land use network under any appropriate dimension specifications and physical constraints guided by any reasonable objective function. Making the process practically applicable to actual development projects may involve more constraints, such as elements of conventional design geometry, and would certainly require an enlarged objective function. Costs would be the first addition, being readily calculated as functions of road and land use configuration. Furthermore the whole character of the modelling result could be changed by including a goal which, for example, seeks a plan with a central focus to the road layout. The only requirement is that each goal must in some way be functionally related to every change in the plan made by the search procedure.

9. Acknowledgement

The modelling work has been carried out by the first author on a scholarship funded by the Australian Research Council and collaborating partners in the Linkage project LP0562422 'Impacts of Transit Led Development in a New Rail Corridor'. The authors thank an anonymous reviewer for directing them to the applicability of the model.

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Appendix 1

Comparison Grid Networks for Square 25 Hectare Area

Grid Model 1

Grid Model 2

Grid Model 3