Integrated planning of linear infrastructure and conservation offsets

J. D. Bunton [a], **A. T. Ernst** [a], **J. O. Hanson** [b], **H. L. Beyer** [b], **E. Hammill** [b], **C. A. Runge** [b], **O. Venter** [b], **H. P. Possingham** [b] and **J. R. Rhodes** [b]

[a]*CSIRO Digital Productivity Flagship, Gate 5 Normanby Road, Clayton VIC, 3168*
[b]*ARC Centre of Excellence for Environmental Decisions, Centre for Biodiversity & Conservation Science, University of Queensland, Brisbane QLD 4072, Australia*
Email: *Joe.Bunton@csiro.au*

Abstract: Linear infrastructure (e.g. roads, railways, utility corridors) is critical to the functioning of modern industrialised societies, but has profound impacts on ecological systems and their biological diversity. The ecological impacts of linear infrastructure may be exacerbated by the failure to anticipate and plan for them early on. Moreover, poor planning can lead to the costly redesign or abandonment of projects to avert unforeseen ecological impacts. Explicitly considering trade-offs between linear infrastructure development and conservation requirements (see Figure 1) at an early planning stage provides the greatest opportunities for achieving both routing and offsetting objectives cost-effectively.

Here, we combine route planning for linear infrastructure with strategic conservation offset decision making in a unified framework to identify efficient opportunities for both routing and impact mitigation. The routing component is spatially explicit and links two or more target nodes via a network of connected planning units with fixed costs while accounting for impacts on features of conservation concern. The offsetting component identifies efficient solutions for mitigating the unavoidable impacts of linear infrastructure. We demonstrate the benefits of solving both planning objectives simultaneously by contrasting the cost-effectiveness of the integrated solutions with those found by solving the problems sequentially.
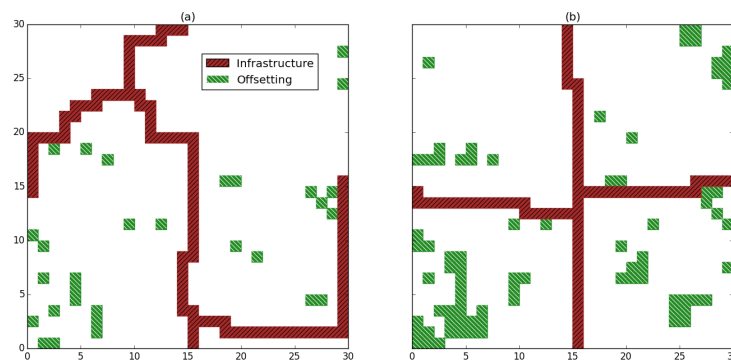

Figure 1. Solutions to a problem instance, favouring (a) offsetting and (b) infrastructure.

We formulated these planning problems in a mathematical optimisation framework in which space is discretised into planning units. Four sets of attributes were quantified for each planning unit as inputs to the optimisation problem: (i) the expected loss of conservation value resulting from linear infrastructure development for each of the conservation features (e.g. species); (ii) the cost of linear infrastructure development; (iii) the cost of offsetting; and (iv) the estimated benefit of offsetting with respect to the conservation features. The decision variables determine whether each planning unit is part of the routing solution, the offsetting solution, or neither. The mitigation effort is required to be sufficient to offset all of the impacts on biodiversity (no net loss) generated by the linear infrastructure development.

We describe an integer linear programming formulation of the optimisation problem and evaluate its efficacy through simulation. We find that solving both problems simultaneously can dramatically improve efficiency compared to solving the routing and offsetting problems sequentially. Furthermore, a sequential approach resulted in infeasible offsetting problems in 25% of cases. This work suggests both linear infrastructure and conservation offset planning could benefit from greater coordination in the early stages of the planning process.

Keywords: Conservation planning, linear infrastructure, mixed integer programming, optimisation, offsetting

1 INTRODUCTION

The global economy depends upon efficient and effective transport infrastructure (Rodrigue et al., 2013), including roads, railways, and pipelines. Maintenance of future economic growth will require construction of new transport infrastructure to meet demand. For example, the construction of more than 25 million kilometres of new roads is anticipated globally by 2050, representing a 60% increase over 2010 levels (Laurance et al., 2014). This unprecedented level of construction has the potential to substantially impact global biodiversity, especially considering the majority of construction is predicted to occur in biodiverse developing nations (Dulac, 2013). The predicted increase in construction of transportation infrastructure, and its potential to detrimentally impact the global environment necessitates the development of strategic planning tools that are able to meet industry demands while minimising environmental impacts. However, existing approaches (e.g. impact assessment, offsetting) focus predominantly on costs, impacts, or ah hoc mitigation, and lack a strategic planning focus.

The direct environmental impacts of linear infrastructure (LI) include loss and fragmentation of habitat, mortality from collisions, disruption of migration routes, chemical pollution and dust, behavioural disturbance, and alterations to the physical environment (Forman and Alexander, 1998; Fahrig and Rytwinski, 2009; Kociolek et al., 2011). Indirect effects include changes to population distribution and abundance, edge effects, invasion by non-native species, further anthropogenic development, and altered species interactions (Fahrig et al., 1995; Saunders et al., 1991; Trombulak and Frissell, 2000). Mitigating such a diverse array of ecological impacts is difficult. Approaches to reducing impacts include strategic routing of LI, providing crossing structures for wildlife (overpasses or underpasses), fencing, imposing speed restrictions in high risk areas, and closing routes during key migration periods. These strategies can be effective at mitigating a subset of impacts arising from linear infrastructure development (Forman et al., 2012).

Many impacts cannot be mitigated, however, and offsetting - protecting or improving habitat in other areas to compensate for these unavoidable impacts - is now widely employed as a framework for balancing development with environmental protection such that, at a minimum, there should be no net loss (NNL) of biodiversity or ecosystem function overall (McKenney and Kiesecker, 2010; Gordon et al., 2011). NNL requires quantification of the losses resulting from development and the benefits resulting from offsetting relative to a baseline describing the expected change in biodiversity in the absence of development (Gordon et al., 2015). Importantly, if the baseline used to quantify benefit is itself a decline in biodiversity over time then biodiversity loss may still result, but not as fast as would have occurred had the development not taken place (Maron et al., 2013). Quantifying a baseline that appropriately captures all dimensions of impact is difficult (Moreno-Mateos et al., 2015) and evidence suggests offsetting may not achieve its stated aim of NNL in practice (Curran et al., 2014; Gordon et al., 2015; Maron et al., 2015). Nevertheless, offsetting is common and can be a major cost in many development projects.

Given that there can be flexibility in LI routing and offsetting options, there is potential to reduce environmental losses and the risk of resulting project delays and design amendments by explicitly considering environmental impacts and offsetting options when planning for LI. In addition, simultaneously carrying out landscape planning and strategic offsetting has been shown to achieve substantial benefits in terms of cost reduction and number of species conserved (Underwood, 2011). Close collaboration between LI design and conservation offsets can be facilitated by providing tools that allow near real-time evaluation of trade-offs between infrastructure and environmental objectives under routing and offset options.

Here, we quantify the efficiency gains that are made possible by combining LI routing and offset selection in the early stages of planning of a development project to address the direct, unavoidable impacts of development on biodiversity. We assume that an appropriate baseline or counterfactual has been identified to quantify both impacts of development and benefits of offsetting (Bull et al., 2014; Maron et al., 2015) and address how this information can then be used to improve planning. Solving both problems simultaneously, which has not been attempted previously, provides opportunities to benefit from changes to LI routing to avoid areas of high biodiversity value that would be costly, difficult or impossible to offset or that could threaten the viability of the project. Where areas of biodiversity are not avoidable, optimal offsetting strategies can be determined.

1.1 Network Design

The hypothetical LI problem considered in this paper is to connect a given set of points with a minimum cost set of intermediate areas. As presented here the cost of building LI is assumed to depend only on the cost of planning areas through which it passes, not on the direction. However including direction-dependent costs

would be trivial in our formulation.

Since we are dealing with a graph induced by the discrete planning units and their adjacencies, the LI routing problem can be considered a subclass of Network Design Problems (NDP). NDP can be formulated generally (Feremans et al., 2003) or more specifically to take advantage of problem characteristics.

The cost of building LI means that the optimal solution will not include any additional links beyond those required to connect the terminals. Hence this is a type of *Steiner Tree Problem*. The Steiner tree problem involves finding the minimum distance network or subgraph that links T points (known as *terminal nodes*) in the Euclidean Plane or on a graph. Intermediate nodes of the connecting network are called *steiner nodes*.

The original motivation for our problem is continuous and could be approached using continuous models (Brazil and Zachariasen, 2015; Demaine et al., 2013). However, based on the discretisation used for the environmental assessment we have a graph. Steiner tree problems on graphs are NP-complete (no quick solution method is known, however solutions can be verified quickly) (Hwang and Richards, 1992). The best known worst case performance for Steiner tree problems on graphs is given by Hougardy et al. (2014), using a dynamic programming approach. Specialised methods, based for example on branch-and-cut, can solve large instances with many hundreds of nodes and thousands of edges (see (Gamrath et al., 2014; Pajor et al., 2014)).

1.2 The Combined Problem

To quantify the efficiency gains obtainable by using a combined approach to LI routing and offsetting, we compare it to the cost of first minimising the LI costs and then the offset costs. That is, we can treat it as a multi-criteria problem or as a hierarchical optimisation problem. For multi-criteria problems there can be multiple pareto-optimal solutions that provide a different trade-off between the two objectives. In our experiments we do not attempt to map out the complete pareto frontier but create solutions using pre-specified relative weights of the objectives.

Hierarchical optimisation involves the treatment of different criteria one at a time. During the first phase offset requirements are ignored. In the second phase the linear infrastructure decisions are fixed and only offsets optimised[1]. The two phase approach results in simpler problems to solve as only decisions relating to the relevant criteria need to be considered. Due to this, solutions achieved are not guaranteed to be globally optimal. This approach mirrors the common practice in LI routing of completing the route planning before commencement of conservation offsetting considerations.

2 PROBLEM FORMULATION

Here we formulate the joint LI routing and offsetting problem as a Mixed-Integer Programming (MIP) problem. The offsetting problem is formulated as a site selection problem similar to the conservation planning software MARXAN (Ball et al., 2009; Watts et al., 2009). The LI routing problem is formulated as a disaggregated Fixed Charge Network Flow problem (FCNF) with no flow costs following the standard practice for steiner tree problems (Goemans and Myung, 1993). Linking the two separate formulations are two sets of constraints: firstly, that each planning unit may may not be both LI and an offsetting zone; secondly, that the offsetting target for the reserve selection problem is the amount of damage to features done by the planning units chosen to be LI.

Using the notation described in Table 1, we can formulate the problem as an mixed-integer linear program. Note that we are only using the minimum number of pairs of terminals to ensure a connected graph.

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[1] A slightly more general bi-criterion method is to bound the cost of the linear infrastructure in the second phase to the minimum achieved in the first phase. For non-uniform costs where the minimum linear infrastructure solution is unique this is expected to be equivalent.

Table 1. Sets, Variables and Parameters for Formulation

Component	Type	Description
I	Set	Set of Planning Units $i \in I$
N_i	Set	Set of Planning Units $j \in N_i$ that neighbours with Planning Units $i \in I$
F	Set	Set of Features $f \in F$
T	Set	Set of terminals $i \in T$ that are to be connected by LI
P	Set	Pairs of flows equivalent to connecting all locations $p \in P$
X_i	Variable	If Planning Unit $i \in I$ is allocated to be a offsetting zone
Y_i	Variable	If Planning Unit $i \in I$ is allocated to be LI
$Z_{i,j}$	Variable	Indicator if both Planning Units $i \in I$ and $j \in N_i$ are offsetting zones
$Fl_{i,j,p}$	Variable	Flow from Planning unit $i \in I$ to $j \in N_i$ for flow $p \in P$
$R^o_{i,f}$	Parameter	Value for occurrence of feature $f \in F$ for Planning Unit $i \in I$
$R^r_{i,f}$	Parameter	Value for restoration of feature $f \in F$ for Planning Unit $i \in I$
C^{LI}_i	Parameter	Cost for allocating Planning Unit $i \in I$ as LI
C^{offset}_i	Parameter	Cost for allocating Planning Unit $i \in I$ for offsetting
b	Parameter	Value for having a boundary between two offsetting zones. As this is a bonus, $b < 0$ is a negative cost
m	Parameter	a constant multiplier that can be used to force the model to achieve greater offsetting benefits than losses (if m>1) to compensate for underestimates in impacts
$v_{i,j}$	Parameter	Value of boundary (i.e. boundary length) between Planning unit $i \in I$ and $j \in I$
$so_{i,p}$	Parameter	1 if Planning Unit $i \in I$ is the source for pair $p \in P$
$si_{i,p}$	Parameter	1 if Planning Unit $i \in I$ is the sink for pair $p \in P$

Objective:
$$\min \sum_{i \in I} \left(C^{offset}_i X_i + C^{LI}_i Y_i + b \sum_{j \in N_i} v_{i,j} Z_{i,j} \right) \tag{1}$$

Flow conservation:
$$\sum_{j \in N_i} Fl_{i,j,p} + si_{i,p} = \sum_{j \in N_i} Fl_{j,i,p} + so_{i,p} \quad \forall i \in I,\ p \in P \tag{2}$$

Only allow flow if LI is built:
$$\sum_{j \in N_i} Fl_{j,i,p} \leq Y_i \qquad \forall i \in I,\ p \in P \tag{3}$$

Fix terminals to be LI:
$$Y_i = 1 \qquad \forall i \in T \tag{4}$$

Can't be both LI and an offsetting zone: $X_i + Y_i \leq 1 \qquad \forall i \in I \tag{5}$

NNL for features damaged by LI:
$$\sum_{i \in I} R^r_{i,f} X_i \geq m \sum_{i \in I} R^o_{i,f} Y_i \qquad \forall f \in F \tag{6}$$

Linearisation of boundary variables: $Z_{i,j} \leq X_i$ and $Z_{i,j} \leq X_j \qquad \forall i \in I,\quad j \in N_i \tag{7}$

Binary Variables: $X_i, Y_i \in \{0,1\} \qquad \forall i \in I$

Continuous Variables: $0 \leq Z_{i,j}, Fl_{i,j,p} \leq 1 \qquad \forall i \in I,\ j \in N_i,\ p \in P$

Equation (1) defines the objective as the sum of the costs of offsetting zones and LI, and the sum of boundary benefits from adjacent offsetting zones. Equations (2), (3) & (4) define the Flows for the LI routing problem, ensuring flow: is conserved, requires LI to be built, and has terminals as the sources and sinks. Equations (5) & (6) link the LI routing and offsetting problems, ensuring planning units cannot be both LI and offsetting zones, and that the offsetting target equals the damage to features from LI. Equation (7) linearises the boundary variables, ensuring the boundary benefit is only given to neighbouring offsetting zones.

3 COMPUTATIONAL STUDY

All tests were performed running the commercial solver software CPLEX 12.5.0.1 on quad octa core 1.87GHz Xeon L7555 processors and 64GB of RAM running SUSE Linux Enterprise Server 11. Each run was

done using 8 cores for 1 hour real time, or until 1.00% MIP gap was reached. The MIP gap is defined as $(ObjectiveValue - ObjectiveBound)/|ObjectiveValue|$ for a minimisation problem such as ours, with a MIP gap of 0 meaning we have an optimal solution.

Each run was specified by a number of parameters: pu - size of planning area, a square of $pu \times pu$ planning units; sp - the number of features being considered (i.e. species); rd - the number of LI nodes to be linked, these are evenly distributed around the edges of the planning area; dam - scaling of LI damage; $ratio$ - the ratio of scaling factors offsetting zone to LI cost ($ratio > 1$ means the offsetting cost is scaled higher than LI cost), which was used to investigate how the relative cost of development and offsetting influenced the solutions. The offset requirement scaling (m) was set to 1 for all problems. Problems instances were solved using both the combined (1 phase) and hierarchical (2 phase) approaches.

For a given set of parameters, planning units were generated and assigned costs for LI and for offset actions. To ensure that the simulated species' distributions were spatially autocorrelated and limited in range size, the presence/absence of each species in the planning units were simulated according to a random Bernoulli process (using a Gaussian covariance model with a scale parameter of 3 and a threshold parameter of 0.3) (Schlather et al., 2015).

Table 2. Mean and standard deviation of MIP gap for 1 phase (combined) problems, and Mean Solve Times (MST) for 1 phase and 2 phase approaches, grouped by different problem characteristics.

	Characteristic	Mean MIP Gap (%)	MIP Gap SD (%)	1 Phase MST (s)	2 Phase MST (s)
$pu =$	15	4.23	4.93	1460	2402
	20	11.34	10.56	2413	2033
	30	21.25	13.45	3131	3185
$sp =$	3	9.68	10.85	1900	2419
	10	16.52	13.54	2771	2740
$rd =$	4	2.18	3.39	1027	885
	6	16.49	11.15	3030	3607
	9	21.59	12.15	2971	3605
$dam =$	1	12.78	11.92	2473	2559
	2	12.87	13.41	2203	2596
$ratio =$	0.01	13.34	11.71	2581	2571
	0.1	13.70	11.68	2633	2553
	1	13.54	11.98	2658	2613
	10	13.54	13.38	2283	2577
	100	11.28	12.67	1973	2536
	1000	11.69	14.23	2013	2618

Table 2 presents the results of our runs, grouping all runs done by different problem characteristics to observe their effects on performance. Most of the complexity of the problem comes from the LI routing Steiner Tree Problem, as shown by the similar mean solve times for the 1 phase vs 2 phase approaches. Problem difficulty is most sensitive to pu and rd. This is intuitive as the parameters increase the difficulty of the more challenging LI routing aspect of the problem, introducing additional constraints and variables due to adding planning units and flows to the problem respectively. Problem difficulty also increases with sp, which increases the difficulty of the offsetting component of the problem. The parameters dam and $ratio$ appear to have had less of an effect on performance.

Figure 2 compares the percentage of problem instances solved under specified MIP Gaps for the 1 phase and 2 phase problems. As the bounds generated in the 2 phase approach are not for the combined problem, the MIP gaps for the 2 phase problems were calculated using the best bounds from the 1 phase approach. There is little difference for the best solved 35% of problems, however better MIP gaps are consistently reached by the 1 phase approach for the rest of the problems. In fact, the 1 phase approach achieves solutions to all feasible problems, whereas the 2 phase approach fails to find a feasible solution for 25% of problems. This 25% failure rate occurs as the LI routing solution initially achieved in the 2 phase approach generates a landscape where offsetting the ecological damage is impossible. This is akin to the real world situation where a proposed LI route is unable to be satisfactorily offset, effectively requiring a complete revision of routing.
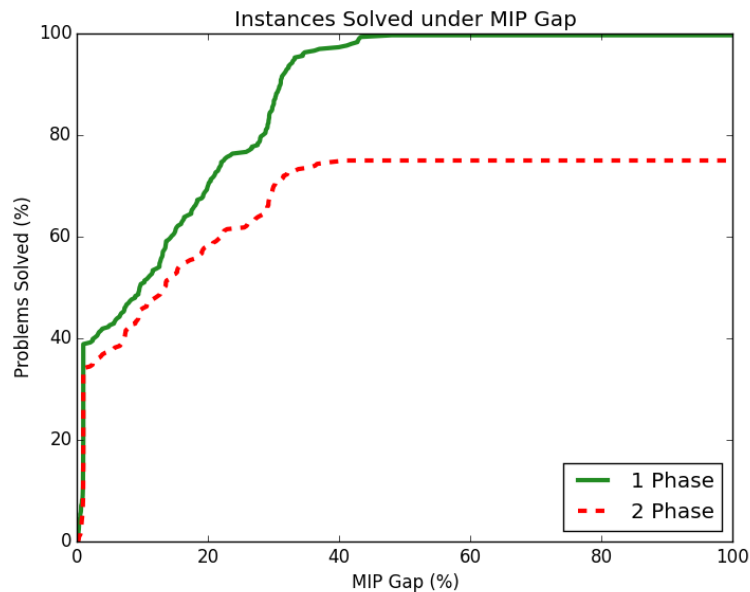
Figure 2. Instances solved below given MIP gap for multi-criteria & hierarchical approaches.

4 CONCLUSIONS AND FUTURE DIRECTIONS

The benefits of the combined approach to LI routing and conservation offsetting include more efficient solutions, lower overall conservation impacts, and increased probability of finding a feasible solution. Specifically, the hierarchical approach generated LI routes that resulted in infeasible conservation offsetting problems in 25% of instances, while the combined approach was universally able to achieve feasible solutions. Although offsetting sites could be selected from a wider area in the real world to achieve a specified target, these results do illustrate the potential benefits of considering both problems simultaneously.

The little difference in mean solve times between 1 phase and 2 phase approaches indicates a small increase in problem complexity by considering offsetting and biodiversity aspects on top of LI planning considerations. This is encouraging as it suggests a low barrier for entry for integrated planning.

While problem difficulty scales quickly with problem size, we are able to solve many reasonably sized problems to near optimality. This may be improved upon with further performance considerations.

Though we have demonstrated several potential benefits of a combined approach to LI routing, this framework would benefit from considering non-localised offsetting, as well as the inclusion of a more realistic treatment of the biodiversity damage calculations, offsetting options, and LI routing constraints.

There is considerable interest in moving towards more strategic landscape-level planning for biodiversity conservation and we have presented a novel approach for achieving this. Both conservation and LI routing objectives can benefit from greater coordination in the early stages of the development process. In many situations the increased costs associated with this planning coordination are likely to be small relative to the potential offsetting cost savings and reduced risk of catastrophic planning failure with respect to environmental impacts. Furthermore, demonstrating that environmental considerations have been formally and quantitatively integrated into the planning process is likely to make planning proposals or contract bids more competitive.

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