PATREC

Multi-Objective Genetic Algorithm Optimisation for Network Widening and Maintenance Scheduling

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[Comments]

Prepared by

Anna Taleb-Bendiab

Chao Sun

Version

Final

About PATREC

The Planning and Transport Research Centre (PATREC) is a collaboration between the Government of Western Australia and local universities, constituted to conduct collaborative, applied research and teaching in support of policy in the connected spaces of transport and land use planning. The collaborating parties are: The University of Western Australia, Curtin University, Edith Cowan University, Department of Transport, Main Roads Western Australia, Western Australian Planning Commission and the Western Australian Local Government Association.

Publisher

Planning and Transport Research Centre
The University of Western Australia (M087)
35 Stirling Highway, Crawley, WA 6009
+61 8 6488 3385
patrec@uwa.edu.au
https://patrec.org/

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1. Project Aims

This project aims to develop a prototype Multi-Objective Genetic Algorithm (MOGA) for planning works across the Western Australian road network. A Genetic Algorithm (GA) is a robust optimisation technique inspired by natural evolution. It is widely used by computer scientists to find high-quality solutions for difficult problems such as scheduling. MOGA is a class of GA that is designed to deal with projects that have conflicting goals, e.g. minimising cost while maximising performance, which means they cannot be simultaneously optimised. A MOGA produces a frontier of solutions that represents the best trade-offs between these goals, from which the user can choose the preferred option.

Although MOGA has many potential applications for Main Roads, this project focuses on a specific use case identified by the client, which is the joint scheduling (in terms of locality and timing) of network widening and maintenance works over a ten-year period. These works will either be completed individually or in combination with other works scheduled for the same area of road. Objectives considered are road safety, overall cost, road user experience and asset condition (Section 4). MOGA minimises costs by integrating works while improving road user experience and safety by targeting the highest benefit roads.

2. Background & Project Motivation

Main Roads Western Australia has recently undertaken a state-wide analysis for regional road widening projects which has identified significant improvements to safety and customer experience. The estimated value of work related to widening work quantified at over $900 million to improve KSI crashes by a factor of 60% to 70%. In parallel, the state's ageing road network typically requires in the order of $100 million per year to maintain. However, investment is only committed where and when needed, without adequate considerations of whether the decision is optimum in terms of risk, safety, function, and best value return. The current use case involves 2,937 works to be scheduled over ten years which results in an enormous number of permutations that is simply too large for humans to deal with. Present methods do not outline a specific methodology which can be interpreted as vague from a corporate level so a more vigorous process is imperative to aid decision making.

Adopting an optimisation process such as MOGA will allow for scheduling of all widening and maintenance works across Western Australia's road network to maximise road user experience and safety while minimising costs and targeting the high priority roads.

The program could be extended to other use cases and the deliverables are expected yield the following possible benefits to Main Roads as an organisation:

- Improving the value return of work programs;
- Improving the efficiency of decision making through automation of processes;
- Promoting a more consistent practice and outcomes across the State;
- Optimising outcome at the whole of network level; and
- Capturing and continuous improvement of corporate operations, knowledge, and decision-making.

A reliable decision-making tool will streamline current decision-making processes with consideration of a collective network view instead of applying ad-hoc rules on a case-by-case basis. Regional input will become a fluid process, as regions will not be required to assess all potential sites but only high priority locations. This systematic process allows sign off at a corporate level to better reflect the Main Roads organisational approach on decision making and achieves better alignment with ISO55000.

3. Datasets Used

Data found in the following Main Roads Excel files were used:

- *Maintenance Works File*: “TYNDP-Condition_Cost_19-03-2020.xlsx”
- *Widening Works File*: “Bretts Widening BCR Whole of state v3.xlsx”
- *Corporate Extract File* (data about the roads): “Corp Ex 2018.xlsx”

The following Excel file was used when comparing schedules generated by the genetic algorithm with those designed manually.

- *Comparison Schedule File*: “RRSIP V2_4.xlsx”

These datasets are provided as input parameters when running the algorithm and can be updated when these datasets change, however certain columns must have the same names to enable the program to read the data correctly (Section 4.1.4).

3.1. Data Cleaning

Maintenance Data

Works are not included in the model in the following cases:

- Works planned for roads in the Metro (‘MET’) region are removed. These are removed from the genetic algorithm completely during data cleaning.

  The following cases are included in the schedules produced by the genetic algorithm but not modelled by the pavement deterioration model:

- Rows with SurfYr of larger than 2020 (there some rows with a SurfYr of 2100)
- Rows with missing values for fields: 'Road', 'Start SLK', 'End SLK', 'Rutting', 'SurfYr', 'Item Description', 'Deflection', 'Curvature', ‘AADT’
- Rows with a surface type of Sprayed Seal but an item description of Resurfacing – Asphalt
- Rows with ‘Road Cat’ that are not one of: 'MFF', 'MI', 'AW', 'BW', 'CW'. Hence roads with Road Categories of ‘V’, ‘DW’ or 0 are not modelled.
- For the road category, AW+ and BW+, road types are treated as AW and BW road categories, respectively.

In addition:

- Rows with missing roughness values are assigned the median roughness value;
- Two columns are also added to the data, one containing the risk factor of the road, and one containing the expected surface life of the road. This is done to prevent recalculating these values in the model;
- When calculating the surface life, the variable Dura is set to 10 for all the roads.

Widening Data

The following data cleaning is performed, these rows are then excluded from the genetic algorithm and its schedules:

- Rows with invalid Existing Seal, Target Seal or Target Pavement values
- Widening works with treatment types of 0 or 5

Corporate Extract Data

Rows with missing AADT values are assigned the mean AADT value of the road that the road section is in. For roads with no given AADT value, the mean AADT value of the network is assigned.

4. Objectives Considered

This section describes the four objectives that are incorporated in MOGA. The program tries to find the best trade-offs between these objectives so that engineers can apply value judgement to choose the final solution.

4.1. Road Safety

This objective aims to maximise the increase in road safety measured by safety savings. This objective is only affected by scheduling widening works since in the safety model only the width and not the asset condition of roads affect safety.

4.1.1. Safety Savings Calculations

The values of savings in terms of road safety are based on the calculations in the *Widening Works File*, which are replicated in the data processing stage of the GA.

4.1.2. User Input

The user running the program can enter the following as input:

- the ROR Severity Index (optional, the default value is 0.591)
- the HOC Severity Index (optional, the default value is 0.756)
- the ROR WTP value (optional, the default value is $1,812,045)
- the HOC WTP value (optional, the default value is $3,590,140)
- and the net change value (optional, the default value is 0.045) which represents the discount factor subtract the crash growth rate.

The default values for these variables are as found in the *Widening Works File*.

4.1.3. Objective Value

The GA uses the cumulative savings in terms of road safety over a thirty-year period as the value of the road safety objective. Therefore, if a widening work is done earlier, it will have higher savings in safety. For example, if a widening work is done in 2020, we use the value of the cumulative savings over 30 years, but if a work is done in 2025, we use the value of the cumulative savings over 25 years.

The value used in the GA to compare the savings in terms of road safety between different schedules is the sum of the savings for all of the proposed widening works in each schedule.

4.1.4. Considerations for Future Work

Currently as the data preprocessing replicates the calculations in the *Widening Works File*, it is dependent on these calculations remaining the same, otherwise the Python script will need to be updated. The program also depends on the name and location of the columns containing the raw data and the worksheet names in the spreadsheet remaining the same.

4.2. Overall Cost

This objective aims to maximise the savings in the overall cost of roadworks in the schedule. The cost can be reduced in two ways, the project cost reduction and savings in delays to road users.

They both occur when roadworks for the same sections of road are combined but the former is a direct monetary saving to Main Roads and the latter is a societal benefit.

4.2.1. Project Cost Reduction

The project cost reduction calculation assumes that combining two or more overlapping projects is more cost effective than doing them separately. The potential savings could come from shared tasks and resources such as traffic management, site set-up, hired equipment.

When a roadwork is scheduled to be completed individually, its original cost is used. If two or more works are scheduled to be done at the same time, the cost of the most expensive work remains the same. For all other works, the cost of the sections of work that overlap with the most expensive work are decreased by a given scaling factor (represented by the variable *overlap_discount* in the program). The cost of the sections of work that do not overlap with the most expensive work are also decreased, but by a lower given scaling factor (represented by the variable *standard_discount* in the program).

In Figure 1, if work A is more expensive that work B and they are scheduled for the same year, then the cost of work A remains the same, the cost of the section of work, B1 would be reduced by the *overlap_discount* ,which has a default of 80% in the program and the cost of the work section B2 would be reduced by the *standard_discount*, which has a default of 20% in the algorithm. These calculations assume an even distribution of cost throughout a work, so the cost of a work section is equal to the proportion of the length of the work section compared to the whole work, multiplied by the cost of the work. These numbers are based on discussions with Main Roads in the absence of relevant data so they should be refined over time.

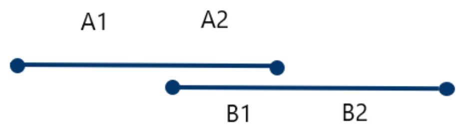

Figure 1 Illustration of the Project Cost Reduction Calculation

4.2.2. Savings in Delays to Road Users

The road user delays reflect the societal cost of roadworks during construction. The methodology is adopted from Section 4.1.1 of Main Roads' Network Performance Analysis for Perth Congestion Response 2017 (PRJ17113, Interim Report by ARRB). The cost is calculated as the product of the delay to road users and the average value of time, which we then also multiply by the number of days a work will take to complete. In the absence of estimated duration for individual projects, the algorithm currently uses the default value 60 days. When two or more projects are combined, the

$$cost\ of\ delay = delay \times value\ of\ time \times number\ of\ days$$

The delay to a road user resulting from a roadwork is calculated as:

$$delay = \frac{section\ length}{reduced\ speed\ limit} - \frac{section\ length}{speed\ limit}$$

Where:
reduced speed limit is the speed limit when roadworks are being completed. The default is set to be 40km/hr;
speed limit is the speed limit when no roadworks is being completed.

The value of time is calculated as:

$$value\ of\ time = value\ of\ travel\ time \times traffic \times vehicle\ occupancy$$

Where:
value of travel time is the average value of travel time per vehicle occupant;
traffic is the AADT value of the road;
vehicle occupancy is the average vehicle occupancy.

When works are completed individually, the cost of delays to road users remains the same. If roadworks are combined, their delays are reduced by the amount that they overlap, as the delays to road users in that section will only occur once rather than twice. In Figure 1, the combined cost of delays to road users is only calculated once for the section A1/B2.

4.2.3. Objective Value

The program calculates the savings in costs of roadworks and the costs due to reduction in delays to road users and uses the sum of these values as the value of the savings maximisation objective used to compare the different schedules.

$$objective\ value = savings\ in\ cost\ of\ roadworks + savings\ in\ cost\ of\ delays$$

4.2.4. User Input

The user running the program can enter the following as input: the *overlap_discount* of roadworks scheduled for the same area of road (optional, the default value is 0.8, giving an 80% reduction in cost), the *standard_discount* of roadworks scheduled for the same area of road but for the sections of roadworks that do not overlap (optional, the default value is 0.2, giving a 20% reduction in cost), the average vehicle occupancy of vehicles in the network (optional, the default value is 1.1) and the value of travel time (optional, the default value is $37.46, which was chosen based on the information given in the ATAP Travel time values for light vehicle occupants[1]). However, commercial vehicles have higher value of time so future work could incorporate vehicle mix for more accurate estimation.

4.3. Asset Condition

This objective aims to maximise the condition of the roads in the networks throughout the ten-year schedule. The condition of the roads is modelled using formulae and data from the “Procedure Pavement Modelling” document.

The pavement health and deterioration of the roads is modelled for the roads included in the *Maintenance Works File*. The roads in the widening schedule are not modelled, unless they are also included in the TYNDP, due to no maintenance works being applied to them.

4.3.1. Asset Condition Calculations

The asset condition of the roads in the network is calculated as follows:

1. The asset condition of all roads at the start of the schedule is calculated by applying the yearly deterioration calculations to each of the metrics rutting, roughness, deflection and curvature from the survey year, which in our dataset is 2018, to the start year of the schedule (2020).
2. For each year in the schedule, the asset condition of the road is calculated, and the pavement health index is added to a running total.
3. If a roadwork is planned in a given year, the treatment reset (see Table 1) of the treatment is applied to the road.

[1] https://www.atap.gov.au/parameter-values/road-transport/3-travel-time

4. The sums of the network pavement health index over the schedule period and the sum of the deterioration of the road are returned and used as the values for the objectives in the multi objective genetic algorithm.

4.3.2. Treatment Resets

When applying treatment resets to the roads in the model, the following mapping from the item descriptions in the TYNDP spreadsheet to the treatments given in the procedure pavement modelling document are used:
'Pavement Rehabilitation' is dTIMS treatment 'Heavy Rehab (GrOL)' (Gravel_OL in the procedure pavement modelling document)
'Resurfacing - Spray seal' is dTIMS treatment 'Sprayed Seal (CS)' ('CS & Enrich' in the procedure pavement modelling document)

Table 1: Treatment Resets

Treatment	Surface Age	Roughness	Rutting	Texture	Crack	Defl	Curv
CS & Enrich	0	N/A	N/A	2	0	N/A	N/A
Slurry	0	0.8* Pre-treatment value	4	1.5	0	N/A	N/A
RipSeal	0	Min(Pre-treatment value, 2.69)	3	2	0	0.88^*D_0	0.78*Curve
Gravel_OL	0	Min(Pre-treatment value, 2.5)	3	2	0	0.64^*D_0	0.58*Curve
ASDG & ASIM	0	Min(Pre-treatment value, 2.88)	1.5	1	0	0.8^*D_0	0.63*Curve
SMA, ASOG, & OGA2	0	Min(Pre-treatment value, 2.88)	1.5	1.4	0	0.8^*D_0	0.63*Curve
ASRH	0	Min(Pre-treatment value, 2.69)	1.5	1	0	0.64^*D_0	0.58*Curve

4.3.3. Pavement Health Index Calculations

The pavement health index is calculated as per the formula in the Procedure Pavement Modelling document and weighted by the road section's length in relation to the length of all sections considered in the TYNDP.

When calculating deflection and curvature, the later enhancement formulae given in the procedure pavement modelling document have been used with the assumption that the values it will be applied to will be in microns.

The weighted pavement health indexes of each road in the TYNDP in each year of the schedule are then added to a running total which is then used by the program to compare solutions.

4.4. Road User Experience

This objective aims to maximise the road user experience throughout the schedule, as represented by Customer Facing Level of Service. The road user experience objective is based on the Travel Experience objective of the Customer Facing Level of Service Model. This objective consists of seven performance indicators, of which three will be modelled in this project: Seal Width, Carriageway Configuration and Ride Quality.

4.4.1. Seal Width & Carriageway Configuration

The data of the seal and pavement widths of the links within the network is found in the *Corporate Extract File*. This is used to determine the levels of service of the Seal Width and Carriageway Configuration performance indicators, given in Table *2* (seal width) and *Table* 3 (carriageway configuration), which are from the Customer Facing Level of Service Rural and Outer Metro Road Network document.

Table 2 : Customer Facing Levels of Service for Seal Width

Level of Service	Carriageway	Link Category	Seal Width (m)
Low	Single	AW+	≤8.0m
		AW	≤7.4m
		BW+	≤6.8m
		BW	≤6.2m
		CW	≤6.0m
	Divided	All	≤NL*3.3
Medium	Single	AW+	>8.0m AND <9.0m
		AW	>7.4m AND <8.0m
		BW+	>6.8m AND <7.4m
		BW	>6.2m AND <6.8m
		CW	>6.0m AND <6.2m
	Divided	All	>NL*3.3 AND <NL*3.5
High	Single	AW+	≥9.0m
		AW	≥8.0m
		BW+	≥7.4m
		BW	≥6.8m
		CW	≥6.2m
	Divided	All	≥ NL*3.5

Table *3*: Customer Facing Levels of Service for Carriageway Configuration

Level of Service	Link Category	Carriageway Configuration
Low	AW+	Single CWY width* ≤ 10.0m
	AW	Single CWY width ≤ 9.4m
	BW+	Single CWY width ≤ 8.8m
	BW	Single CWY width ≤ 8.2m
	CW	Single CWY width ≤ 8.0m
Medium**	AW+	Single CWY, max 3 lanes, CWY width > 10.0m
	AW	Single CWY, max 3 lanes, CWY width > 9.4.0m
	BW+	Single CWY, max 3 lanes, CWY width > 8.8m
	BW	Single CWY, max 3 lanes, CWY width > 8.2m
	CW	Single CWY, max 3 lanes, CWY width > 8.0m
High	All	Dual CWY OR single CWY with multiple lanes***

4.4.2. Ride Quality

The ride quality performance indicator in each year is based on the roughness values of the road, which is taken from the values calculated in the asset condition calculations with treatment resets being applied if a maintenance work is scheduled for that year. The level of service is then based on the values in Table *4*, from the Customer Facing Level of Service Rural and Outer Metro Road Network document.

Table 4: Customer Facing Levels of Service for Ride Quality

Level of Service	Link Category	Roughness - IRI (m/km)
Low	MI, MFF	>3.4
	AW+, AW	≥ 3.8
	BW+, BW	≥ 4.2
	CW	≥ 5.3
Medium	MI, MFF	>2 and <=3.4
	AW+, AW	> 2.2 AND < 3.8
	BW+, BW	> 2.6 AND < 4.2
	CW	> 3.0 AND < 5.3
High	MI, MFF	<2
	AW+, AW	≤ 2.2
	BW+, BW	≤ 2.6
	CW	≤ 3.0

4.4.3. Objective Value

The value that is used to compare the road user benefits between different schedules is a sum of the Customer Facing Levels of Service for each year over the ten year period for the network, scaled by the length of the road in comparison with the network and the AADT value of the road, giving the area under a curve for the Customer Facing Levels of Service. Hence schedules which schedule the works that result in the largest increase in Customer Facing Levels of Service earlier in the schedule will have higher overall values for the road user benefits objective.

5. Scheduling Constraints

5.1. Environmental Approvals

Initially the environmental impact of the maintenance and widening works was planned to be an objective. However, as the data of the environmental impact of proposed works was not available, the environmental impact is considered as a constraint. Widening works that require clearing (treatment types 4 and 5) need to have environmental assessments done in order to get approval to complete the works. As such in the program, widening works that involve clearing have the constraint of not being scheduled within the first two years of the schedule, to allow time for any required environmental approvals to be processed.

5.2. Maintaining Asset Condition

When scheduling the years to carry out maintenance works, a constraint that the program will apply will be to ensure that the roads are kept in an acceptable condition. This will be done by evaluating the rutting and roughness of the roads in the network for each year in the schedule and using the amount that these metrics are above given acceptable values as an objective value when ranking solutions.

5.2.1. Calculating Deterioration Values

As with the asset condition objective, the pavement deterioration values (*Table* 5) are calculated from 2018, (the year that the survey was carried out), up to the first year in the schedules (2020). If the deterioration values for the metrics rutting and roughness (and not deflection or curvature) are above the acceptable levels for their road category (as given in Table 6) for years during the schedule (2020-2029), the difference between the value of the metric and the value of the acceptable level is added to a running total representing the total deterioration of all of the roads in that solution. This value is then used to compare the overall deteriorations of solutions when evaluating which solutions should be used in the next iteration of the algorithm.

Table *5*: Cracking Values used for calculating deterioration values

Cracking Values	Meaning	Condition
0	no cracking	The surface age is less than 1.1 of the surface life expectancy.
1	minor cracking	The surface age is more than 1.1 and less than or equal to 1.3 of the surface life expectancy.
2	major cracking	The surface age is more than 1.3 times the surface life expectancy.

Table 6: Acceptable deterioration levels

Road Category	Roughness	Rutting
MFF & MI	3.44	15
AW	3.82	15
BW	4.2	15
CW	5.33	15

5.3. Widening and Maintenance Budget Constraints

This constraint ensures that the widening and maintenance works scheduled are always within their respective yearly budgets, with a combined allowance of how much schedules can be over budget in each year. The yearly budgets used in the program for maintenance and widening works are $150 million and $100 million respectively, and the amount that the schedules can be over budget in each year is $10 million combined between the maintenance and widening works.

The maintenance works scheduled also have the constraint to not be more than $10 million under budget in each year, however this is not applied to the widening works.

6. Schedule Selection

The schedules are selected from the set of schedules on the Pareto front during each iteration in the genetic algorithm. First the Pareto optimal solutions are selected from this set, then schedules are selected as follows:

Schedules 0-4 are selected by k-means clustering, using the library Scikit-learn.
Schedule 5 has the most discount in cost
Schedule 6 has the highest savings in safety
Schedule 7 has the highest PHI scores
Schedule 8 has the highest Customer Facing Level of Service scores
Schedule 9 has the lowest levels of deteriorations of the roads
Schedule 10 meets the maintenance budget the most closely.

The choice of which schedules to select can be changed in the results processing file (RunProcessResults.py) depending on which objectives we would like the best schedules for and how many schedules should be selected by k-means clustering.

7. Results

7.1. Final Schedules

7.1.1. Objective Results

Upon analysing the resulting schedules we found that the variation in the objective scores (See Appendix A: Objective Results of Delivered Schedules) was smaller in certain objective values than others, for example, in the asset condition and road user experience objectives we found that there was very little variation between the best and worst schedules for those objectives. With the difference in average PHI between the best and worst schedule in that objective being 0.02008 and the difference in the percentage of the roads with high or medium average customer facing level of service being 0.5817%. However, for the safety and maximising cost objectives the differences are much larger. With the safety objective having a range of $213,076,006 and the range in values of the maximising cost savings objective being $120,170,437.

We think that the reason for these differences is due to the budget constraints. Given the budgets that were used, all the maintenance works were able to be scheduled at some point in the schedules, with the differences in PHI scores being due to the year that the works are scheduled. However, there were more widening works than the budget allowed for, hence some works were scheduled, and some were not. We think this selection of different widening works to be scheduled is what is causing these differences in objective scores.

7.2. Comparison with Provided Schedules

A comparison of schedules generated by the genetic algorithm with those designed by Main Roads was also conducted. The schedule from Main Roads only included widening works, found in the "MOGA" worksheet of the *Comparison Schedule File*. Due to only widening works being included in the schedules, only the objectives of Road User Experience and Safety were included in the optimisation, and only seven schedules were delivered, with five being selected through K-means clustering, one schedule with the highest safety savings and one with the highest road user experience objective score. As seen in Figure 3, the results of this comparison show higher levels of customer facing levels of service, and a range of safety savings values, some higher and some lower than the provided schedule. The objective values of these schedules are as seen in Appendix B: Objective Results of Compared Schedules.

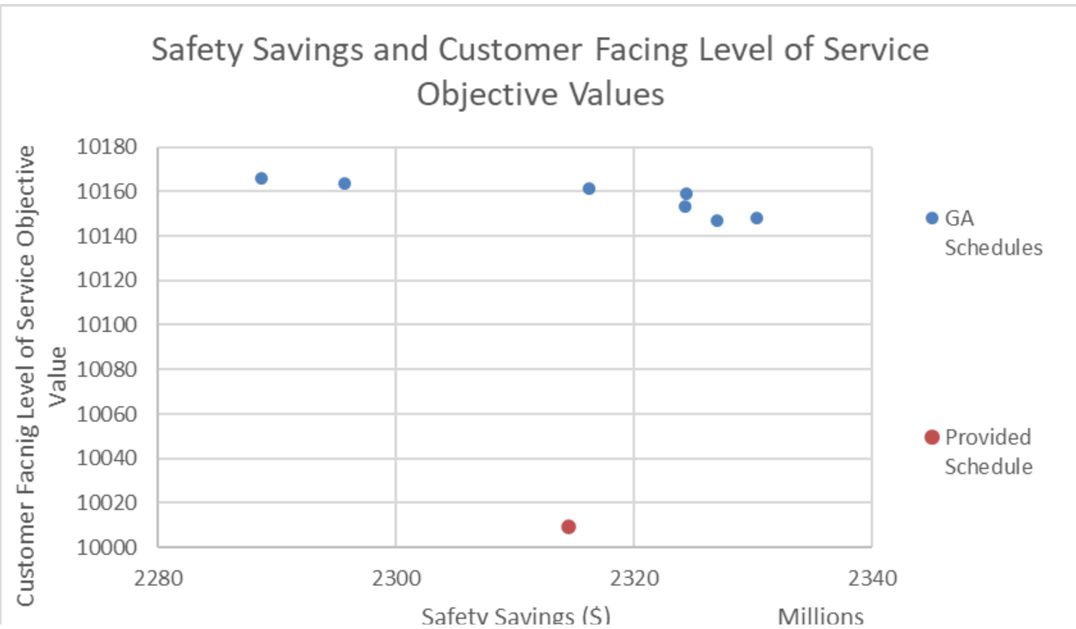

Figure 3: Comparison between GA Schedules and Provided Schedule

8. Deliverables

8.1. Potential Schedules

The program developed in this project will generate schedules of maintenance and widening works. These schedules will schedule the widening and maintenance works over the next ten years (from 2020 to 2029, inclusive), which is the timeframe that the TYNDP schedules maintenance works over.

A set of potential schedules of the widening and maintenance works will be delivered to Main Roads, along with metrics of each of the objectives for each of the solutions and visualisations representing these metrics. Main Roads can then select their preferred schedule using these metrics and visualisations.

8.2. Executable File

An executable file, allowing the user to run the genetic algorithm will also be provided. It will allow the user to change any parameters of the genetic algorithm such as: the number of iterations for the genetic algorithm, the population size, and the willingness to pay value used when calculating the savings in terms of safety of a solution. A GUI (graphical user interface) is not required by the client.

8.3. Python Code

The Python 3.6 code developed in the project, which runs the genetic algorithm, including data processing, objective models and schedule selection will be delivered to Main Roads. This code will contain a README file detailing how to run the program and will be commented throughout. The programs can be run from the command line using the commands given in the README file.

8.4. User Manual

A user manual will also be provided, which will explain how one can run the genetic algorithm. It will include information such as: the inputs required, the parameters that the user can change and the output.

8.5. Presentation and Workshop

A workshop has been conducted during which the work was presented to key stakeholders.

9. Future Work

9.1. Combined Cost Model

One area of improvement of this project is in the model used in the combined cost model. Currently a simple model (See Section 4.2) has been devised to calculate a savings when combining two roadworks, this model is made of two components, which could each be improved in the following areas:

9.1.1. Reduction in Cost of Works

Currently the model considers a flat reduction in cost of overlapping sections of works. An improvement to this would be to consider different reductions in cost, depending on the type and size of the works being scheduled.

9.1.2. Reduction in Delays to Road Users

Currently this component of the model uses constant values for the following variables:

- Cost of user time
- Vehicle occupancy
- Number of days taken to complete a roadwork
- Reduced speed where roadworks are being completed

The cost of user time and vehicle occupancy could be modified to reflect the different types of vehicles and their corresponding occupancies and cost of user time for each road. The number of days taken to complete a roadwork could be modified to reflect the size and type of the roadwork being carried out. The reduction in speed could also be modified depending on the type of roadwork being scheduled, the original speed of the road and could also factor in that roadworks are not completed at night and that the difference in reduction in speed is usually staged (slowly decreased rather than decreased straight to 40km/hr).

9.2. Road User Experience Model

The road user experience model could be extended to also incorporate the results from the road user surveys.

9.3. Asset Condition

Currently the asset condition is calculated as a sum of the PHI scores of the network over the ten-year period, we could test increasing the length of this period that the asset condition is considered over.

9.4. Other Application Areas

Although this program has been developed for a specific use case, the general concept of Multi-Objective Optimisation has many potential applications for Main Roads, especially when complex scheduling, resource allocation, and trade-offs between conflicting objectives are involved. For example, the program could be extended to include geometry improvements for the road safety program.

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Appendix A: Objective Results of Delivered Schedules

Schedule Number	Work Cost	Delay Costs	Cost Objective Value	Safety Savings	PHI Objective Value	CFLOS Objective Scores	Average PHI	Percentage Average Low LOS	Percentage Average Medium LOS	Percentage Average High LOS
0	$ 2,187,005,562.62	$ 715,065,353.14	2902070916	2495420817	25.064	51226.290	4.2412	0.0320	0.6863	0.2818
1	$ 2,191,774,589.49	$ 711,216,902.04	2902991492	2497490994	25.152	51234.848	4.2562	0.0271	0.6764	0.2965
2	$ 2,194,944,841.91	$ 705,812,322.77	2900757165	2483126766	25.137	51233.536	4.2535	0.0262	0.6772	0.2966
3	$ 2,183,893,716.28	$ 702,276,347.46	2886170064	2482483126	25.109	51188.775	4.2489	0.0280	0.6756	0.2964
4	$ 2,195,728,795.75	$ 704,384,423.48	2900113219	2491301878	25.124	51192.288	4.2513	0.0262	0.6773	0.2965
5	$ 2,151,633,516.80	$ 697,082,463.61	2848715980	2415898265	25.085	51189.617	4.2535	0.0262	0.6776	0.2963
6	$ 2,222,958,827.24	$ 745,927,589.77	2968886417	2570620867	25.101	51171.822	4.2562	0.0262	0.6774	0.2964
7	$ 2,217,086,450.14	$ 710,999,968.70	2928086419	2429898855	25.183	51236.206	4.2613	0.0262	0.6776	0.2963
8	$ 2,184,505,560.53	$ 695,968,466.20	2880474027	2357544861	25.152	51243.801	4.2561	0.0262	0.6772	0.2966
9	$ 2,209,317,666.49	$ 705,101,298.09	2914418965	2525258618	25.111	51206.247	4.2579	0.0265	0.6774	0.2961
10	$ 2,198,605,535.62	$ 710,008,840.98	2908614377	2492113074	25.074	51174.173	4.2428	0.0262	0.6776	0.2963

Appendix B: Objective Results of Compared Schedules

Schedule Number	Safety Savings	CFLOS Scores	Percentage Average Low LOS	Percentage Average Medium LOS	Percentage Average High LOS
0	$ 2,295,699,888.14	10163.859	0.0187	0.8398	0.1416
1	$ 2,324,266,442.33	10153.282	0.0194	0.8391	0.1416
2	$ 2,324,354,490.01	10159.016	0.0194	0.8391	0.1416
3	$ 2,326,949,581.16	10146.844	0.0194	0.8391	0.1416
4	$ 2,316,238,246.60	10161.580	0.0194	0.8391	0.1416
5	$ 2,330,288,701.79	10147.962	0.0194	0.8391	0.1416
6	$ 2,288,662,559.23	10165.926	0.0194	0.8495	0.1311
	Safety Savings	CFLOS Scores	Percentage Average Low LOS	Percentage Average Medium LOS	Percentage Average High LOS
Provided schedule from Main Roads	$ 2,314,527,194.04	10009.468	0.0265	0.8796	0.0939