ALGORITHMIC AND SIMULATION-BASED OPTIMISATION OF BLADING MAINTENANCE OF A GRAVEL ROAD NETWORK

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ABSTRACT

Gravel roads are maintained by an activity called blading, which entails the redistribution of surface material over the road surface using a mechanical grader. Blading may be performed dry or wet, depending on the condition of the road surface, and compacting of the graded road may also be required in some cases. The required frequency of blading is a function of the road usage pattern and the properties of its surface material. Emergency blading may be required when a road was damaged by natural phenomena or an abnormal usage pattern. The Provincial Government of the Western Cape (PGWC) is supporting research aimed at the optimization of blading activities on its gravel road network. To start off an investigation was undertaken to determine the constraints and variables that would determine the domain within which optimised routes for blading teams might be determined. Based on the results of this investigation, two possible solution techniques were devised and a third possibility identified through a literature study. The constraints and variables of the particular problem are described as well as the possible solution techniques. The merits of simulation-based optimisation are compared to those of directly solved algorithmic optimisation.

1. INTRODUCTION

The Provincial Government: Western Cape (PGWC), Department of Transport and Public Works is currently in the process of developing a management system, known as the Gravel Management System (GMS). This system forms part of other data management systems currently used by the PGWC. The GMS can be classified as an operational level system assisting PGWC staff, District Municipality managers and Consulting Engineers with the scheduling and management of activities related to the gravel road network under the jurisdiction of the Provincial Administration. See Figure 1 for the relation of the GMS to the other systems at PGWC.

During the compilation of the User Requirement Specification (URS) for the GMS, the need was identified to incorporate a tool that would assist the District Municipalities (DM’s) with the optimisation of their blading program.

The purpose of the Blading Optimisation Module (BOM) is to assist operational level managers to optimise routine maintenance work on the gravel road network.

This paper is divided into four main parts. The first part focuses on the results of an investigation that was undertaken to define the variables and constraints under which blading maintenance is undertaken on the gravel road network. The second part focuses on the possible solution methodologies that were developed to address the PGWC’s and DM’s needs. In the third part simulation is defined and a comparison is made between blading optimisation based on simulation and algorithmic determination of an optimised schedule. Part four contains some conclusions.

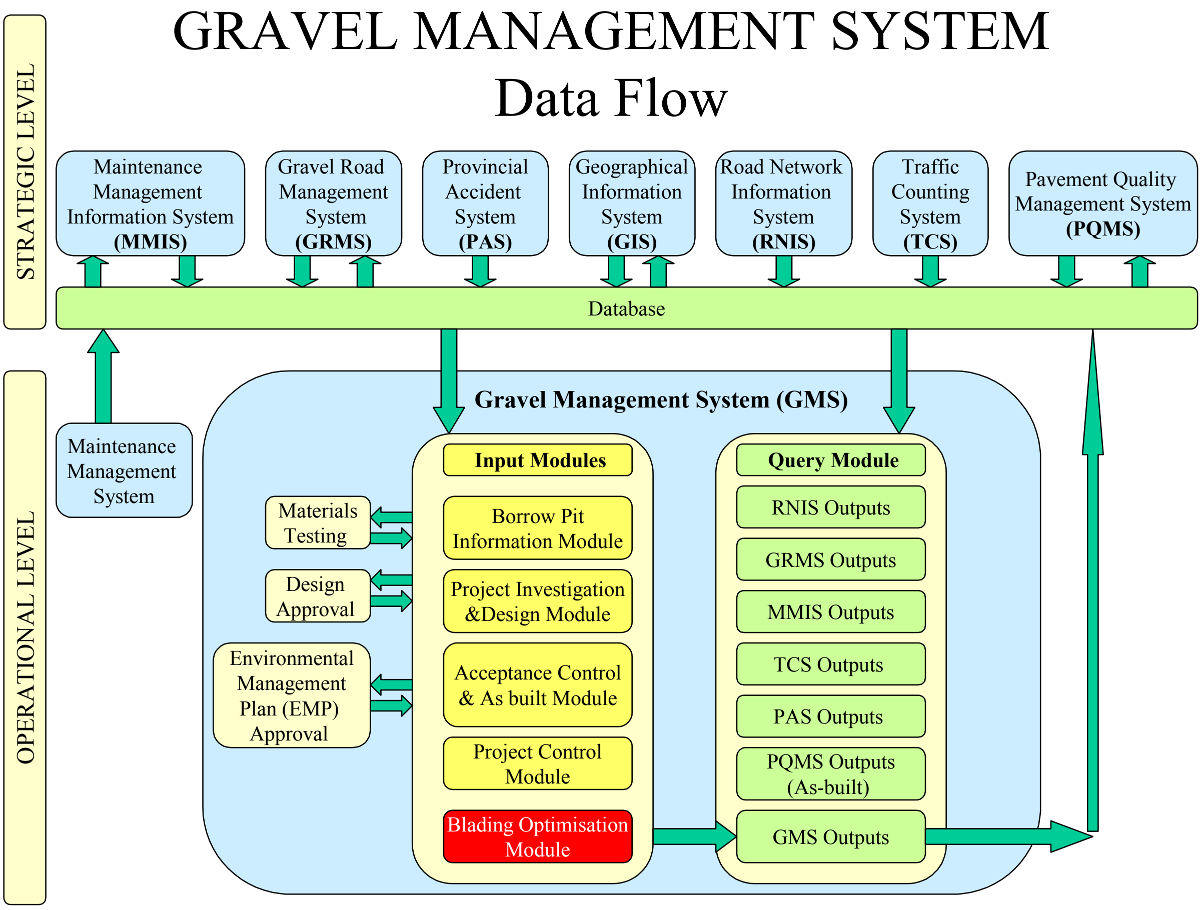

Figure 1. Relation of GMS to PGWC's other systems. [1].

2. PART ONE: DETERMINING THE PROJECT CONSTRAINTS AND VARIABLES

2.1 Introduction

The Province of the Western Cape is divided into 5 DM's whose geographical areas is a decomposition of the geographical area of the Western Cape. Each of the DM's is responsible for the maintenance of the road network in its area. The road network is comprised of sealed roads and gravel (unsealed) roads. *[The term gravel road is used generically, although not technically correct. In fact approximately 15% of the total gravel road network of the PGWC is earth graded roads (i.e. a gravel wearing course was not imported onto these roads).]*

The DM personnel in each of the DM's were interviewed to determine the constraints and variables applicable to the project. The results of the interviews are reported in this part of the paper.

2.2 Network Sub-Division

Each of the DM's is divided into regions and these regions are further divided into maintenance wards. In each of the maintenance wards there are at least one mechanical grader used for the blading maintenance of the gravel roads in the ward.

The boundaries of the wards are determined by the DM's and may vary in terms of the total kilometres in each. However, it was found that the DM's are divided to have approximately equal ward sizes (in terms of kilometre road maintained) within a ward.

Thus, a blading team is responsible for the maintenance of a part of the total gravel road network of the PGWC.

2.3 Blading Teams

The blading maintenance is performed by the blading team and this team consists of the grader and a water bowser (if wet blading is required). The personnel complement is typically comprised by the grader operator, water bowser operator and two labourers.

2.4 Blading Methodology

A number of blading types were identified during the interviews.

The types are:

- Dry blade: blading without a water bowser on site.
- Wet blade: blading with a water bowser on site.
- Rain blade: blading after good rains have fallen.
- Cushioning blade: spreading of a thin layer of fine material over the road surface to protect the wearing course.
- Reshaping: breaking down of road surface and shaping at the required cross-fall to improve drainage on the road. Water bowser and (usually) a Pneumatic Tyre Roller (PTR) on site.

The type of blading applied depends on the general condition of the road prior to blading, weather conditions on day of blading, the terrain in which the section is located and the blading strategy of the specific DM.

Blading strategy refers to the strategic planning of the DM's. Certain roads within a DM may have strategic value to the community and these roads may need to be bladed at pre-determined times during the year. For instance, in the grape producing areas the roads on the main transport routes from the farms to the cellars/cold stores may be bladed just before the start of harvest time. In other cases, the DM may have a policy of doing a wet blade on all the roads in the DM just before the rain season starts. This ensures minimal pothole formation because the roads have sufficient drainage capacity, thus protecting the wearing course (road shape is good).

2.5 Blading Frequency

A number of factors are taken into account when the DM's determine blading frequencies. These factors are:

- Traffic (Annual Average Daily Traffic – AADT)
- Gravel Quality (and wearing course thickness)
- Tourism
- Link Road
- Climate (Weinert's N-value – a climate indicator used widely in southern Africa)
- Type of Agricultural activities (Sensitive or Non-sensitive activities)

It should be pointed out that none of the DM's followed a formalised calculation procedure based on material and traffic variables to arrive at blading frequencies. The majority of the DM's determine blading frequencies for specific roads based on past experience. However, one of the DM's did start to calculate blading frequencies based on the budget available to perform routine maintenance on the roads. This calculation is based on a type of utility analysis where the total budget is distributed to a road based on the ratio of the road's score to the total score for all roads in the area. The amount allocated to a road for the financial year is then divided by the cost to perform blading maintenance on the road, thus resulting in a blading frequency for the road.

From the above it is clear that none of the DM's make use of material-based deterioration models to calculate blading frequency. However, it has been found over time that the blading frequencies used by the DM's result in average road condition acceptable to the road users.

2.6 Blading Scheduling
Blading maintenance is not formally scheduled by the DM's. However, as mentioned earlier specific roads in a DM area may be bladed at pre-determined times due to the DM's maintenance strategy.

The DM personnel have very good communication with the blading teams. In general, they know on a day-to-day basis where the teams are working. The DM's all have monthly planning meetings and at these meetings the blading maintenance program for the coming month is discussed and agreed upon. The program is then communicated to the blading teams in the different wards.

In addition to the blading maintenance program, the teams have to respond to emergencies as and when they occur and also to complaints from the public. Due to the nature of gravel roads they are very susceptible to damage, e.g. flash floods or abnormally high traffic volume (e.g. due to an auction somewhere on the road), and need to be repaired as soon as possible when damage occurs.

2.7 Summary of Facts
The facts mentioned in the foregoing paragraphs are summarised in Table 1– some additional detail gathered from the interviews are also contained in the table.

Table 1. Summary of pertinent facts obtained from interviews. [2].

Aspect	District Municipality				
	Eden	**Overberg**	**Boland**	**West Coast**	**Central Karoo**
Blading frequency based on a calculation	Yes	No	No	No	No
Blading frequency based on past experience	Yes	Yes	Yes	Yes	Yes
Length of gravel and earth roads (Proclaimed Roads) [km]	3 066	1 400	1 250	2 509	2 499
Number of maintenance wards	15	7	5	13	4
Number of maintenance graders	15	7	5	13	5
Typical Dry Production Rate [km/day]	8	7	10	10	10
Typical Wet Production Rate [km/day]	1	3.5	5	5	5
Approximate average blading frequency [Number per year]		3 - 4	4	10 - 11	4 - 6
Maximum blading frequency [Number per year]	13	4	6	11	6

3. PART TWO: PROPOSED SOLUTION ALGORITHMS

3.1 Proposed Solution Algorithm 1
This section contains an algorithm that was developed to address the problem of programming the blading teams in the different maintenance wards to achieve an acceptable level of service (acceptable roughness level on average) while minimising the cost of providing the service. The algorithm is based on the assumption that blading teams blade segments of a road and move between segments.

3.1.1 Objective
The objective of the District Municipalities is to **minimise the average network roughness, while minimising the cost** to do this. Thus, this objective may be defined as **minimising the Total Transportation Cost (TTC)**, where TTC is defined as the sum of Agency cost and Road User cost.

Agency cost is the cost incurred to provide a certain level of service to the public. Agency cost is in this case defined as the difference between the cost to perform routine maintenance and the cost to do nothing. (Routine maintenance cost: salaries, monthly plant rental cost, plant running cost, plant maintenance cost; Do nothing cost: salaries and monthly plant rental cost.)

Road User cost is calculated by using Vehicle Operating Cost (VOC) formulae. VOC for a given road is directly dependent on the roughness of the road.

3.1.2 Variables

The following variables are important for the implementation of the solution algorithm:

- Type of blading applied: Dry or Wet (including the production rate associated with the blading type).
- Speed of travel between segments.
- Blading frequency per segment.
- *Condition of segments at the start of the analysis cycle.*

3.1.3 Algorithm

The proposed algorithm is summarised in the steps listed below (see also Figure 3):

1. Divide the DM road network into its wards.
2. Divide each road into its visual assessment segments (as in GRMS).
3. For each segment, assign values for the variables during the analysis cycle.
    3.1 Blading type
    3.2 Condition in terms of category: VG, G, F, P, VP. Converted internally to IRI/QI value.
4. Specify the production rates for wet and dry blading.
5. Specify the travel speed.
6. Determine a schedule (time based sequence) for the analysis cycle as follows:
    6.1 Start at the worst segment*. The user may also specify the start segment.
    6.2 Calculate the time necessary to travel to and blade that segment. Increment the time used with the time used to blade the segment. Increment the cost by the cost to blade the segment.
    6.3 Check if any segment exceeded the maximum time allowed** between blades during the time to blade the previous segment. If a segment exceeded the maximum time allowed, go to step 6.5. Else, go to step 6.4.
    6.4 Search for next worst segment, keeping in mind that the other roads deteriorated during the time that the previous segment was bladed.
    6.5 Determine the shortest route to reach the next segment (measured in time units).
    6.6 Calculate the time to blade segment. Increment the time used with the time to reach the segment and to blade the segment. Increment the cost with the cost to blade the segment.
    6.7 Start again at step 6.3.
    6.8 Repeat steps 6.3 to 6.7 until all segments have been bladed the required number of times or the time used is equal to the cycle length.
7. Calculate cost for schedule determined in step 3; calculate average roughness of ward network during analysis period.
8. Calculate the VOC for the given roughness per segment
9. Sum VOC for all segments to obtain VOC for network.
10. Calculate the TTC.
11. Decide if schedule is acceptable. If schedule is not acceptable return to step 6 and start at a different segment.

**Worst segment*: The criteria to determine the worst segment will need to be defined. It is proposed that each segment in a ward is assigned a weight (similar to Eden DM procedure) and then the weight and current condition may be used to determine the worst segment.

**Maximum time allowed*: This is the blading interval (the inverse of the frequency) measured in preferred time units (e.g. days, weeks, months).

The two (opposing) objectives of the DM are addressed in the algorithm. The acceptable schedule will be the one that results in the best average network roughness while at the same time it will minimise the cost associated with rendering the service.

The deterioration of the segments is used to determine when a segment will be bladed. The function will have to be set up such that the maximum allowable roughness is reached when the time elapsed since last blade is equal to the blading interval (the inverse of the frequency). It is proposed that a sigmoidal function be used for the modelling of roughness deterioration (see Figure 2). The function will be set up such that it starts at time zero (just after blading) at a roughness value set by the user. The road then deteriorates until the maximum allowable roughness is reached when the time elapsed since last blade is equal to the blading interval. This deterioration modelling is purely empirical and based on the experience of the DM personnel.

Roughness deterioration may, however, also be modelled based on other functions (e.g. TRH20 functions, HDM4 functions). The system will be developed such that it is possible to select the method of deterioration modelling.

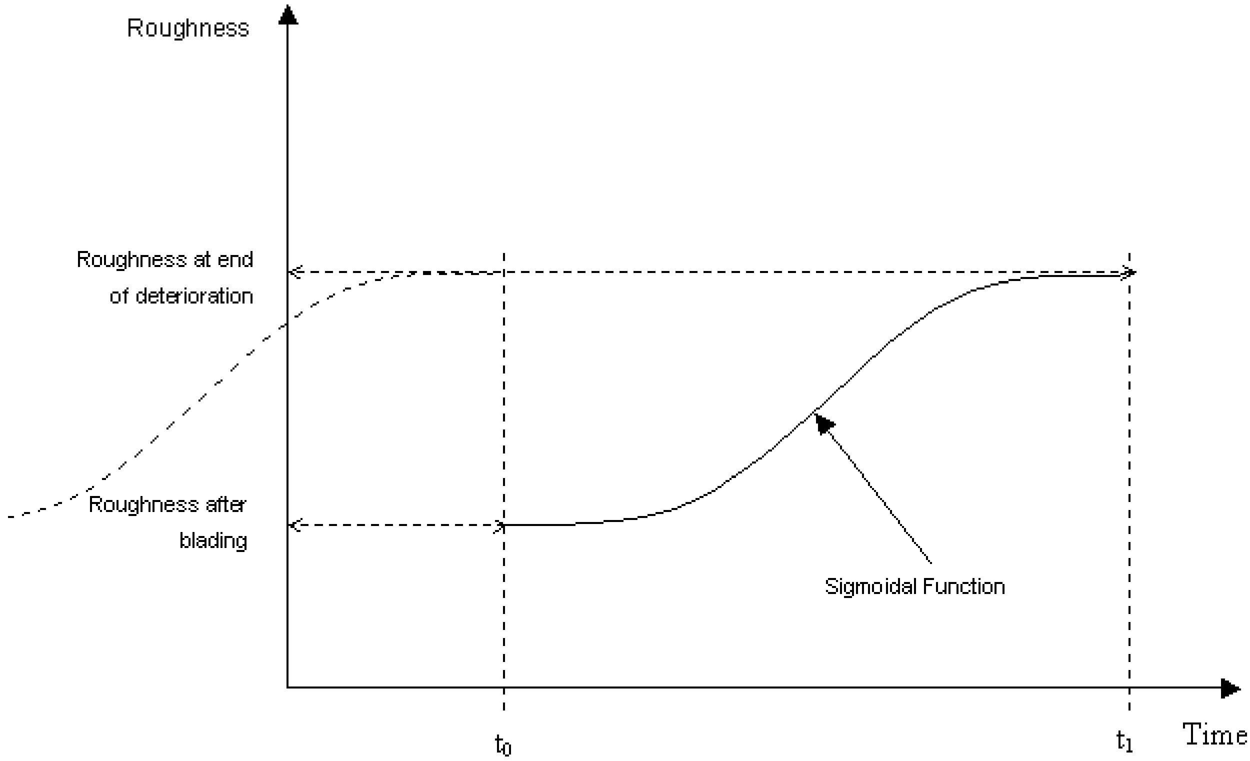

Figure 2. Sigmoidal deterioration function.

3.1.4 Further Algorithm Refinements

It might be possible that optimum schedules (as determined by the method above) may be optimised further by adding more levels of complexity to the algorithm.

This means that the algorithm may be changed so that the system not only searches for the next worst segment, but the segment next in line after the next worst segment is also determined. The schedule is then determined where the grader moves to the next worst segment. The schedule is also determined where the grader moves to the second next worst segment and from there to the next worst segment. (Thus, the order in which segments are visited is changed.) The TTC is then calculated for both the normal schedule and the schedule where segment visits are changed.

However, these further refinements should not be included at first. It is proposed that the algorithm is first implemented to the satisfaction of all parties before adding any levels of complexity.

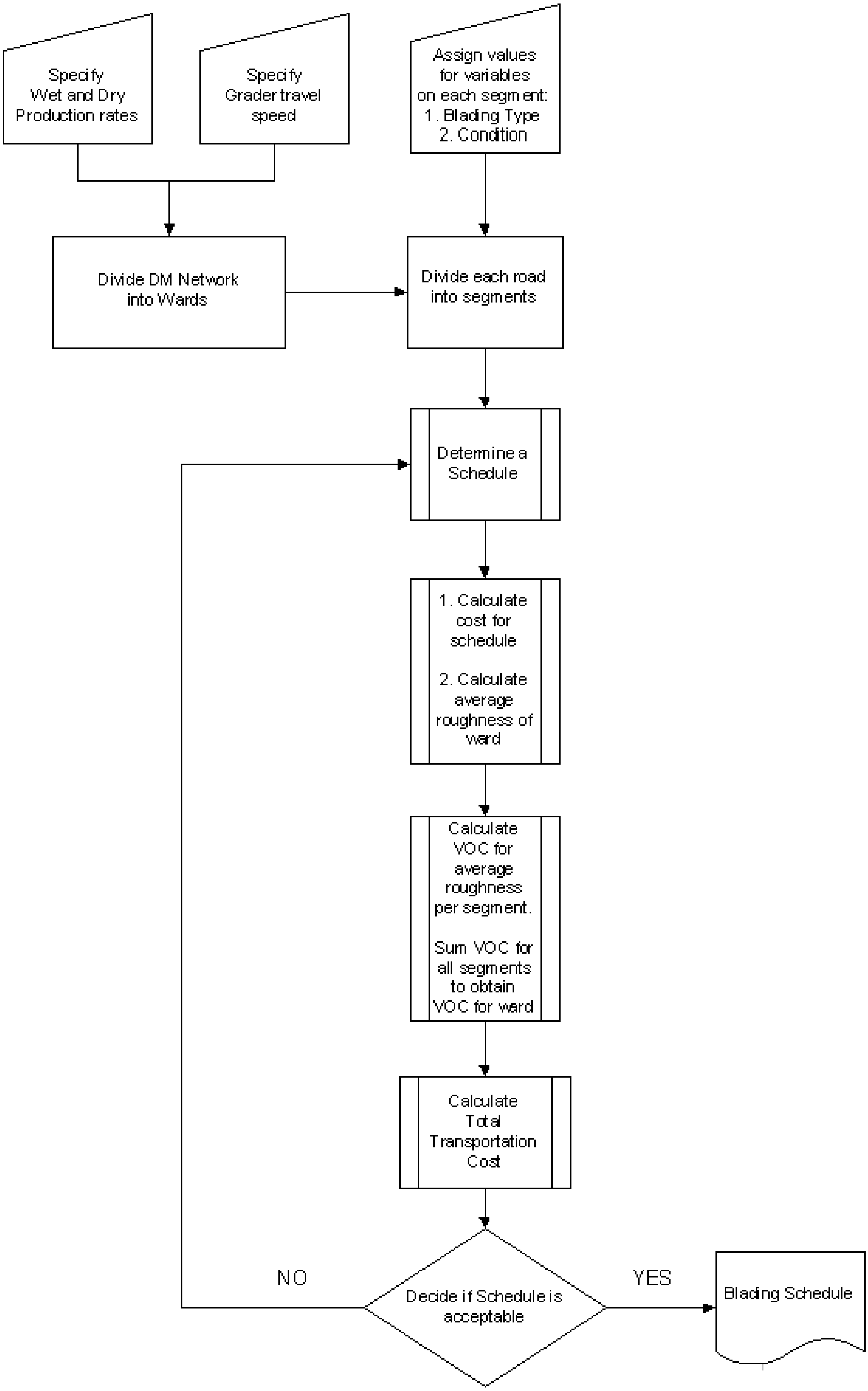

Figure 3. Flow chart for Algorithm 1.

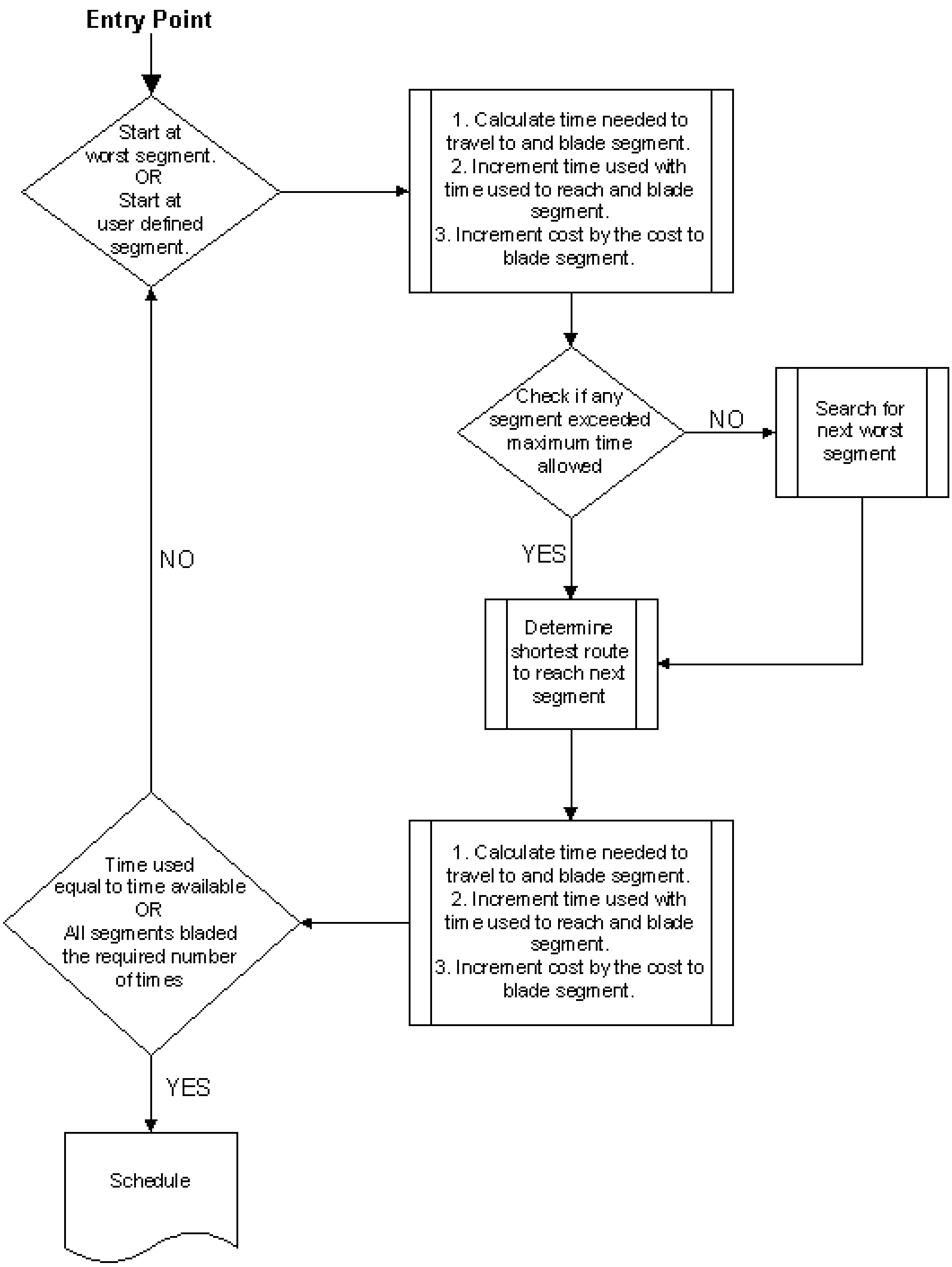

Figure 4. Algorithm for "Determine Schedule" step in Algorithm 1.

3.2 Proposed Solution Algorithm 2

The algorithm described in this section aims at determining the schedule in a ward that will satisfy the need to provide the best average roughness for the ward network. Furthermore, the blading teams start with a road and finish blading the whole road (or the required sections on it) before moving to the next road.

3.2.1 Objective

The objective of this algorithm is to **minimise the network roughness**. The cost of the solution does not influence the decision to accept or reject the solution.

3.2.2 Variables

The following variables are important for the implementation of the solution algorithm:

- Type of blading applied: Dry or Wet (including the production rate associated with the blading type).
- Speed of travel between segments.
- Blading frequency per segment.
- *Condition of segments at the start of the analysis cycle.*

3.2.3 Algorithm

The proposed algorithm is summarised in the steps listed below (the first number of steps are essentially the same as for Algorithm 1). (See also Figure 5):

1. Divide the DM road network into its wards.
2. Each Road in a ward is further sub-divided into its visual assessment segments (as in GRMS).
3. Assign values for the variables during the analysis cycle:
   3.1 Indicate if blading is required during the analysis period.
   3.2 Blading type (if required during analysis period).
   3.3 Condition in terms of category: VG, G, F, P, VP. Converted internally to IRI/QI value.
4. Specify the production rates for wet and dry blading.
5. Specify the travel speed between segments.
6. A start road is input by the user.
7. The system determines all possible routes (i.e. routes that traverse all the required segments) through the network. The number of routes is a function of the network structure.
   7.1 For each route, the network condition is calculated as a function of time. The average roughness for the cycle is also calculated.
8. User chooses a route or enters a different start road.

As with Algorithm 1, road deterioration has to be modelled to obtain the average roughness of the network over the analysis cycle. Again the deterioration may be based on an empirical method, or on the TRH20 or HDM4 methods.

<u>3.3 Proposed Solution from Literature</u>

During the time that the interviews were conducted, it came to the attention of the authors that a Ph. D. study was in the process of being finalised at the University of Stellenbosch. The subject of the study is scheduling and routing a service in a network. The research was conducted by Mr. George Groves under the guidance of Profs. J. H. van Vuuren (US) and J. le Roux (UNISA).

The problem from practise that led to the research being conducted is described in this section, together with the solution algorithm developed for the problem. The information described here was obtained from [3].

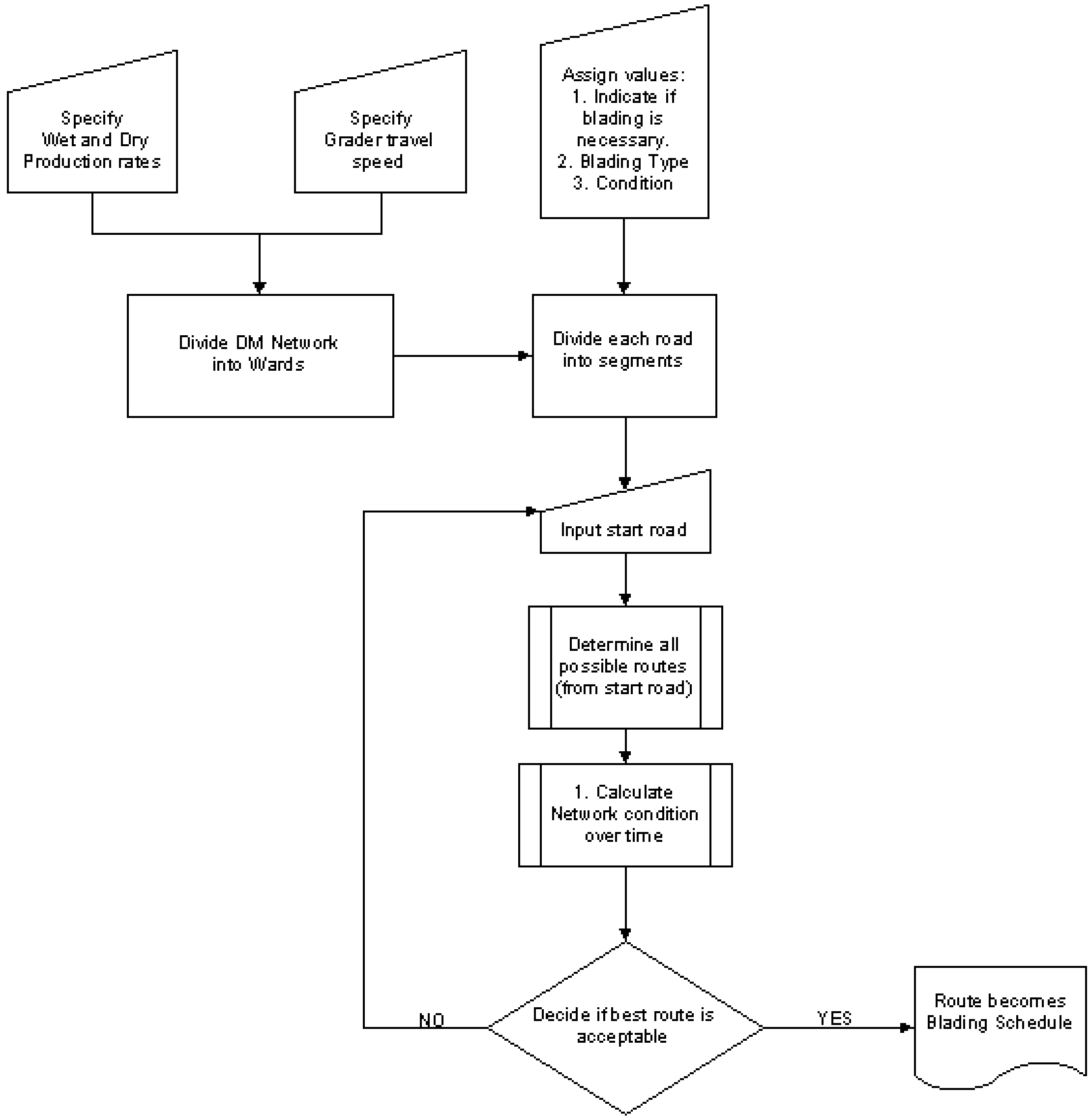

Figure 5. Flow chart for Algorithm 2.

3.3.1 Problem Statement

The problem statement reads as follows: "Given a transportation network – a subset of its edges has to be serviced, each edge a specified (potentially different) number of times."

The problem arises from the fact that SPOORNET has one machine that conduct certain measurements on its rail network. (Similar to visual assessments.) The machine is not required to return to a depot every night. Furthermore, it has to visit specified rail sections on a regular basis and the frequency of the visits is based on the rail track class of the section. (Class is determined by the track width, allowable axle weight and some other criteria.)

A graph based heuristic was developed to address the problem and provide optimised solutions for the schedule of visits and minimising the cost of the schedule.

The problem faced by the service inspector is to determine:

- a closed service route through the network
- that services some subset of the network links
- visiting each link in the subset at least a pre-specified (potentially different) number of times

- while simultaneously minimising the total servicing cost
- and achieving an acceptable amount of temporal spread with respect to consecutive services of the same link, for all network links, over the scheduling time window.

4. PART THREE: COMPARING ALGORITHMIC SOLUTION METHODOLOGY TO SIMULATION SOLUTION METHODOLOGY

In this section a short overview of simulation is given. Blading optimisation, as described in this paper, is then discussed by comparing (1) a simulated solution procedure with (2) a directly solved solution procedure.

4.1 Background to Simulation

In order to understand how blading optimisation may be simulated, it is first necessary to define the term simulation. Furthermore, simulation procedures are based on constructed models of real-world processes/systems. Thus, some background information pertaining to simulation modelling is also presented.

4.1.1 Definition of Simulation

Banks [4] defines simulation as: "Simulation is the imitation of the operation of a real world process or system over time. Simulation involves the generation of an artificial history of the system and the observation of the artificial history to draw inferences concerning the operating characteristics of the real system that is presented."

Simulation may be used to describe existing systems; analyse the behaviour of the systems; do sensitivity analyses on the systems (ask what-if questions); and it can be used as a tool to design new systems.

Thus, simulation endeavours to mimic real-world systems or processes as closely as possible so that system behaviour (and by implication, performance) may be predicted over time and so that the behaviour may be analysed.

4.1.2 Simulation Modelling

Pritsker [4] quotes Simon and comments as follows regarding modelling: "*'Modelling is a principal – perhaps the primary – tool for studying the behaviour of large complex systems… When we model systems, we are usually (not always) interested in their dynamic behaviour. Typically, we place our model at some initial point in phase space and watch it mark out a path through the future.'* Simulation embodies this concept because it involves playing out a model of a system by starting with the system status at an initial point in time and evaluating the variables in a model over time to ascertain the dynamic performance of the model of the system."

Models of systems may be scaled down physical objects (representing the components of the system) – called *iconic models*; it may be a collection of mathematical equations and relations – called *abstract models*; or it may be a graphical representation – called *visual models*.

Modelling is greatly aided if physical laws are available that pertain to the system; a graphical representation can be made of the system; and the uncertainty in system inputs, components and outputs is quantifiable.

On the other hand, modelling complex, large-scale systems is usually more difficult than modelling a strictly physical system for one or more of the following reasons:

- Few fundamental laws are available
- Many procedural elements are involved which are difficult to describe and represent
- Policy inputs are required which are hard to quantify

- Random components are significant components
- Human decision making is an integral part of such systems

Simulation models may be classified as discrete-change, continuous-change or combined models. These are defined on the basis of the major independent variable in most models: time. Generally, in most models time is the independent variable with other system variables functions of time. The values of the dependent variables are used to calculate system performance measures.

Discrete models have dependent variables that change only at distinct points in simulated time (event times); continuous models have dependent variables that are continuous functions of time; in combined models the dependent variables may change discretely, continuously or continuously with discrete jumps superimposed.

4.2 Fitting Blading Optimisation into the Picture

Based on the foregoing discussion, it is possible to define the model for optimising blading maintenance as a combined model.

Roads deteriorate continuously over time and the state of a road section (riding quality) is set to a new value at discrete points in time (when the grader visits the section). System performance for algorithm 1 is calculated based on both the network riding quality over time and the cost of blading the network over time. For algorithm 2 system performance is calculated as a function of network riding quality over time.

4.3 Simulation Procedure for Blading Optimisation

The procedure for optimising blading maintenance through simulation is as follows:

- User chooses a sequence of sections to be bladed.
- System runs through calculations for the sequence.
- Network performance is reported in terms of the performance measure(s).
- User then modifies the first sequence or chooses a new sequence. Alternatively he accepts the sequence.

Through such an iterative procedure, the user may obtain a blading sequence close to (or being) an optimal blading schedule for his network.

4.4 Merits of Simulating Blading Maintenance

By using a simulation procedure (as described above) the user quickly develops a “feel” for what is happening to the network when different blading sequences are chosen. This is based on evaluating the performance measures for different sequences. By asking what-if questions and analysing the results, the effects of different decisions/scenarios are made clear to the user.

Furthermore, the user will take ownership of system output (since he was so closely involved in obtaining it). Incident to this, the system is accepted much easier since the user is able to work with and develop knowledge of how system outputs are obtained (the user develops confidence in the system).

On the other hand, if the user is given a system that “kicks out” output without any user interaction system acceptance is negatively affected. This is in part due to the fact that the algorithms presented in this paper may result in schedules that optimise the network performance measures, but the schedule requires a user paradigm shift on how maintenance is performed. This means that the user may not have confidence in the system.

Thus, allowing the user to "play" with the system (i.e. asking what-if questions and performing sensitivity analyses) results in greater acceptance of the output obtained by directly solving for the optimised schedule. Accepting output leads to confidence in the system and acceptance of the system.

5. PART FOUR: CONCLUSIONS

The Blading Optimisation Module (BOM) of the Gravel Management System (GMS) of the Provincial Government: Western Cape (PGWC) was described in this paper. A short overview of the GMS and where the BOM fits into it was given.

The results of interviews conducted to determine the constraints and variables pertaining to the BOM was reported. Based on the results of the interviews, two algorithms were developed that could be used to optimise blading maintenance in the Western Cape. A third algorithm was identified from literature – the applicability of this algorithm still has to be ascertained.

Simulation and simulation modelling was defined. Based on the definitions given it is possible to show that the model for optimising blading maintenance is a combined model – the dependent variables change continuously over time (riding quality deterioration) and component states are changed at discrete times (riding quality reset to a pre-determined value when section is bladed by grader).

The merits of simulating blading maintenance was also discussed. It was shown user acceptance of the new system may be greatly enhanced if the users are allowed to input their own blading schedules; change blading schedules; ask what-if questions; and compare simulation output to directly solved output.

6. ACKNOWLEDGEMENTS

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