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Leading-Edge Asset Management

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Whole Life Cost Optimisation Model for Water distribution Systems: Case Study of Kampala City, Uganda.

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Presentation Layout

- Background
- Problem Identification
- Research Objectives
- Research Methodology
- Problem Formulation
- Application/Results/ Discussion
- Conclusions/Recommendations

Introduction

- Whole life costing(WLC) – seeks to optimise the cost of rehabilitating/operating the physical assets over their useful life.
- WLC –recognises that initial costs represent a minor portion of the overall costs incurred throughout the lifetime of an asset
- Optimization – technique used to efficiently evaluate a number of solutions by altering the details of a system to generate new / improved solutions
- Decision support tool for adoption of cost-effective solutions

Problem Identification

- Repair and replacement of aging water mains impose big expenditures on water utilities – the need increases as old pipes continue to deteriorate.
- Budget provisions for rehabilitation of assets are inadequate – therefore available funds should be used in a cost effective way
- Number of rehabilitation alternative solutions is large, exploring all possibilities ensures that a cost-effective solution is found.

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Research Objectives

- Develop an optimal WLC rehabilitation & maintenance strategy of water distribution assets using an integrated WLC optimizer
- Application of WLC to a small zone within Kampala City water distribution network

Methodology

- Hydraulic modeling of Mbuya zone network – Kampala City (Arc GIS/EPANET 2)
- Integrating hydraulic model with a WLC optimizer with an in-built Genetic Algorithm (GA) search technique
- Application of the integrated WLC optimizer to Mbuya Zone network – Kampala City

Problem Formulation

- Minimize the WLC of system rehabilitation while maintaining an acceptable level of service
- Period of analysis was 25years split into 5-year time segment
- Decision variables are the rehabilitation options – replacement, cleaning and No-action

Problem formulation continued

- Cost functions for decision variables – present value method with discounting (accompanied by sensitivity analysis)
- No-Action option (C1) - Repair costs were considered
- Cleaning option (C2) - Repair costs + cleaning costs
- Replacement option (C3) - Repair costs + Replacement costs

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Problem Formulation continued

- No-action Repair Costs (C1):
  $C1 = (BR(d_i,t)*BC(d_i)*BCF*l_i*5)/(1+r)^{5t}$

  $BR(d_i,t)$ = failure rate for diameter d_i at time step t (bursts/km/year) – $y = aX^b$ (Constatine & Darroch, 1995)

  $BC(d_i)$ = burst cost (US$) for Kampala

  BCF = burst cost factor for indirect costs (traffic disruption etc)

  l_i length of pipe i (km); t is the time step (0,1,2,3..5)

  r is the discount rate

Problem Formulation continued

- Replacement Costs (C2) = $(R(d_i)*l_i)/(1+r)^{5t})$

  Rd_i = unit cost of replacing pipe with diameter d_i (US$/m)

  $Rd_i = d_i^{0.6}$ for comparing costs of different pipe diameters.

- Cleaning Costs (C3) = $(0.06*d_i^{0.6}*l_i)/(1+r)^{5t})$

  $0.06d_i^{0.6}$ = unit cost of cleaning pipes (US$/m)

- Minimize Whole life System rehabilitation costs = C1+C2+C3

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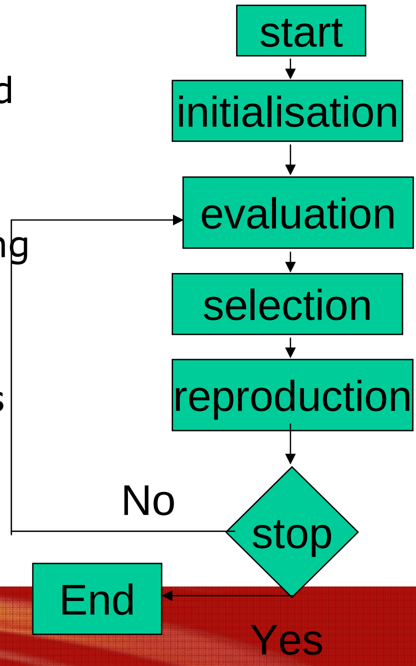
Optimization Method

- Genetic Algorithm
  - search technique developed by Holland
  - based on Darwins' theory of evolution
- Uses natural selection as a driving force
- Allows automation of the decision making
- Requires each variable to be defined to the decision maker's satisfaction
- GA has achieved fame among engineers for its ability to identify good solutions



Whole life cost (WLC)optimisation

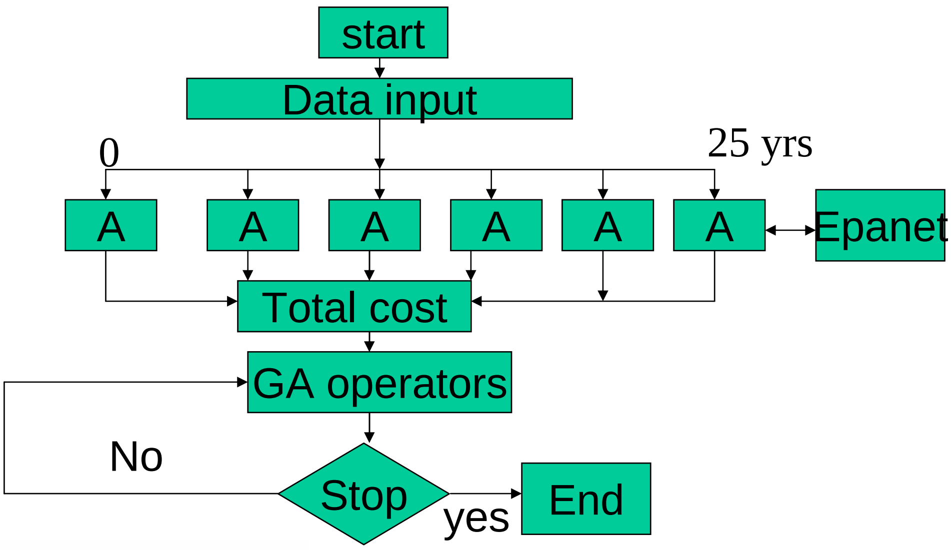
- The multiple time step problem
- Minimise WLC cost = $\sum_{t=1}^{5} system(\cos t_t)$

where system cost = $\sum_{y=0}^{N} Cost_y(d_i)$

-where $cost_y(d_i)$ = C1+C2+C3

- N is the number of pipes in the network

Whole life cost optimisation routine



WLC Optimization

- Initialization

  A - random selection of decision variables at a time step,
  B - computation of network rehabilitation cost,
  C - hydraulic simulation
  D – computation of total network cost including penalty.

Finally compute total rehabilitation cost over the analysis period

WLC Optimization continued

- Penalty cost = $\sum_{i=1}^{N} \gamma \left| H_{\min} - H_{actual} \right|$
- H_{min} = minimum allowable pressure
- H_{actual} = actual nodal pressure
- N = number of pressure violating nodes

Other constraints: Conservation of mass and energy in a loop

- Rehabilitation strategies with no pressure violation at all nodes will have zero penalty; high fitness and greater chances of surviving to the next generation

Application to Case Study Network:

- Kampala City Water Supply Service Area
  - Cover area 250km^2, Population 1.35m inhabitants, water production 130,000m^3/day, transmission network 100km, distribution system 1,700km
  - condition of network has deteriorated (poor operating practices, insufficient funds for rehabilitation)

- Hydraulic modeling of Mbuya zone distribution network
  -3.17 km of mains, supplying 1,600 conns. (population ca.13,000)
  -13pipes(steel&plastic) , diameter (40mm-100mm)

Application continued

- C-Factor could not be measured in the field
- Walski et.al 1998 model used

C-Factor(t)=18 – 37.2 log $\frac{e \ + a_i(t + g_i)}{D_i}$

e – initial roughness of pipe (m) – 0.18mm

t – time elapsed from present to future periods (yr)

a_i-roughness growth rate (m/yr) – 0.2mm/yr

D_i – diameter of pipe i(m)

Case Study Network Data

- Network data for Mbuya zone – Kampala City

Node	Elevation (m)	Demand (l/s)	Pipe No	Connecting nodes		Diameter (mm)	Length (m)
1	1181	2	14	1	2	100	230
2	1187	8.5	2	2	3	100	200
3	1182	8	3	3	4	50	415
4	1200	7.5	4	4	5	40	282
5	1196	3	5	2	6	100	426
6	1210	7	6	4	6	100	160
7	1235	5.7	7	6	7	100	95
8	1255	6.2	8	7	8	100	353
9	1250	4.2	10	7	10	80	83
10	1195	6.4	9	8	9	50	226
11	1249	6	11	8	11	80	295
12	1194	5.1	12	11	13	100	215
13	1260	5.7	13	11	12	50	190

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Case Study Network Data Continued

- Pipe Data

Pipe No	Pipe Material	Pipe Age(yr)	C-Factor
2	Plastic-PVC	35	95
3	Plastic -PE	34	84
4	Plastic-PE	34	80
5	Steel	34	95
6	Plastic-PVC	34	95
7	Steel	34	95
8	Steel	33	96
9	Steel	28	86
10	Plastic-PVC	32	92
11	Plastic-PVC	25	95
12	Plastic-PVC	25	88
13	Plastic-PVC	24	100
14	Steel	35	95

Results

- GA Parameters

- Population size 100, Mutation rate 0.1, crossover rate 0.8, maximum generation number 2000, Tournament size 5 and a discount rate of 6%

- Program was run 20 times and strategy with the least cost is shown in the table that follows

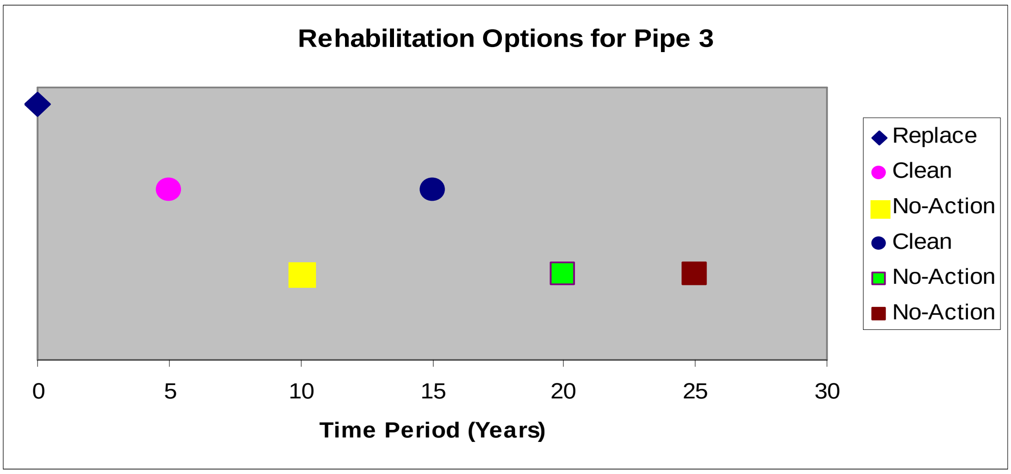
Rehabilitation options

Pipe \ Time	0 year	5years	10years	15 years	20years	25years
14	Cleaning	Cleaning	Cleaning	Cleaning	Cleaning	Cleaning
2	Cleaning	Cleaning	Cleaning	No-Action	Cleaning	Cleaning
3	Replace	Cleaning	No-Action	Cleaning	No-Action	No-Action
4	No-Action	Replace	No-Action	Cleaning	Cleaning	No-Action
5	No-Action	Cleaning	Cleaning	Cleaning	Cleaning	No-Action
6	Cleaning	No-Action	Cleaning	Cleaning	Cleaning	Cleaning
7	Cleaning	Cleaning	No-Action	Cleaning	No-Action	Cleaning
8	No-Action	No-Action	Cleaning	Cleaning	Cleaning	No-Action
10	Cleaning	Cleaning	No-Action	Cleaning	Cleaning	No-Action
9	Cleaning	No-Action	Replace	Cleaning	Cleaning	Cleaning
11	Cleaning	No-Action	Cleaning	Cleaning	No-Action	Cleaning
12	Cleaning	Cleaning	Cleaning	Replace	Cleaning	Cleaning
13	Cleaning	Cleaning	Cleaning	Cleaning	Cleaning	Cleaning

Break rate of pipes (bursts/km/yr)

Pipe \ Time	0 year	5years	10years	15 years	20years	25years
14	1.702	2.180	2.720	3.323	3.988	4.719
2	1.702	2.180	2.720	3.323	3.988	4.719
3	0	0.036	0.153	0.357	0.655	1.045
4	2.205	0	0.039	0.168	0.395	0.723
5	1.614	2.079	2.607	3.197	3.851	4.568
6	1.614	2.079	2.607	3.197	3.851	4.568
7	1.614	2.079	2.607	3.197	3.851	4.568
8	1.528	1.982	2.497	3.074	3.715	4.419
10	1.765	2.304	2.917	3.607	4.375	5.219
9	1.874	2.520	0	0.036	0.153	0.358
11	1.136	1.571	2.079	2.663	3.322	4.058
12	1.534	2.120	2.807	0	0.036	0.153
13	0.867	1.210	1.614	2.079	2.607	3.197

Rehabilitation options for pipe 3



Discussion

- The break rate is determined by when the pipe is replaced – age reduces to zero.
- For pipes with diameter > 50mm, the break rates at end of analysis period is between 4–5.2 bursts/km/yr & average break rate for the entire system at the end of the analysis period is 3.25 bursts/km/yr
- For smaller pipes, failure rate was between 0.1 – 1.1 bursts/km/year using replacement option, thus it is cost-effective to replace at some point in time other than keep repairing and cleaning

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C-Values of pipes with time

T pipe	0 years		5 years		10 years		15 years		20 years		25 years	
	B	A	B	A	B	A	B	A	B	A	B	A
14	58	120	90	120	90	120	90	120	90	120	90	120
2	58	120	90	120	90	120	90	90	80	120	90	120
3	48	120	79	120	79	79	69	120	79	79	69	69
4	45	45	42	120	75	75	65	120	75	120	75	75
5	60	60	57	120	90	120	90	120	90	120	80	80
6	60	120	90	90	80	120	90	120	90	120	90	120
7	60	120	90	120	90	90	80	120	90	90	80	120
8	60	60	57	57	56	120	90	120	90	120	90	90
10	56	120	86	120	86	86	76	120	86	120	86	86
9	50	120	79	79	69	120	79	120	79	120	79	120
11	60	120	86	86	76	120	86	120	86	86	76	120
12	52	120	79	120	79	120	79	120	79	120	79	120
13	64	120	90	120	90	120	90	120	90	120	90	120

Discussion

- Replacement and cleaning options restore the C-value of the pipes whereas the No-Action option has no effect.
- C-factors initially decrease rapidly for new and recently cleaned pipes and change more gradually after a few years.
- C-value decreases more rapidly in small diameter pipes compared to large pipes

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Limitations

- Model addresses activity based accounting – no account for life cycle assessment (social & environmental costs)
- Water demand assumed constant and pipe replacement done using same diameter & material
- Two options considered (cleaning and replacement)
- Inadequate O & M data to predict network performance more accurately

Conclusions

- Structural and hydraulic deterioration models based on available historic data are important to predict future asset performance
- Optimization techniques can identify least cost solutions for various O & M scenarios.
- WLC is a decision support tool and must be backed up by sound engineering and economic judgment from decision makers.

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Recommendations

- Comprehensive Pipe condition prediction models need to be developed and incorporated in the optimization tool
- Extended to include increases in system demands and consider diameters of pipes for replacement as a decision variable.
- Screening at each time step to ascertain pipe condition is necessary before assigning rehabilitation options.
- As annual funds available to utilities are limited; there is need to include budget constraints at time steps (multi-criteria objectives)

Thank you