A SCHEDULING MODEL

FOR

A COAL HANDLING FACILITY

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An operational scheduling model for Sasol Coal Supply

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SUMMARY

A scheduling model for a coal handling facility

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Scheduling; Mixed Integer Non-Linear Programming; MINLP; Coal handling facility; Continuous time representation; Event based scheduling; GAMS; Operational solution time; SOS1 variables; NLP linearization.

Summary:
The objective of this project is to develop an operational scheduling model for Sasol Mining's coal handling facility, Sasol Coal Supply (referred to as SCS), to optimise daily operations. In this document, the specific scheduling problem at SCS is presented and solved using Mixed Integer Non-Linear Programming (MINLP) continuous time representation techniques.

The most recent MINLP scheduling techniques are presented and applied to an example problem. The assumption is made that the results from the example problem will display trends which will apply to the SCS scheduling problem as well. Based on this assumption, the unit-specific event based continuous time formulation is chosen to apply to the SCS scheduling problem.

The detail mathematical formulation of the SCS scheduling problem, based on the chosen technique, is discussed and the necessary changes presented to customise the formulation for the SCS situation. The results presented show that the first phase model does not solve within 72 hours. A solution time of more than three days is not acceptable for an operational scheduling model in a

dynamic system like SCS.

Various improvement approaches are applied during the second phase of the model development. Special Ordered Sets of Type 1 (SOS1) variables are successfully applied in the model to reduce the amount of binary variables. The time and duration constraints are restructured to simplify the structure of the model. A specific linearization and solution technique is applied to the non-linear equations to ensure reduced model solution times and reliable results.

The improved model for one period solves to optimality within two minutes. This dramatic improvement ensures that the model will be used operationally at SCS to optimise daily operations. The scheduling model is currently being implemented at SCS. Examples of the input variables and output results are presented.

It is concluded that the unit-specific event based MINLP continuous time formulation method, as presented in the literature, is not robust enough to be applied to an operational industrial-sized scheduling problem such as the SCS problem. Customised modifications to the formulation are necessary to ensure that the model solves in a time acceptable for operational use.

However, it is proved that Mixed Integer Non-linear Programming (MINLP) can successfully be applied to optimise the scheduling of an industrial-sized plant such as SCS. Although more research is required to derive robust formulation techniques, the principle of using mathematical methods to optimise operational scheduling in industry can dramatically impact the way plants are operated. The optimisation of daily schedules at SCS by applying the MINLP continuous time scheduling technique, has made a significant contribution to the coal handling industry.

Finally, it can be concluded that the SCS scheduling problem was successfully modelled and the operational scheduling model will add significant value to the Sasol Group.

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CHAPTER 2:

NOMENCLATURE

The variables used in every chapter are listed. Some variables are redefined in consecutive chapters. Therefore, the variables used in more than one chapter are duplicated in the list below.

CHAPTER 2:

Cap_s_j	capacity of stockpile j
$Cost_i$	cost of conveying coal from mine i
Delta	the size of an interval in the discrete time representation
Demand	coal demand of factory during time horizon
Dur_b_{ijp}	duration of conveying coal from mine i to stockpile j if it starts at point p
Dur_r_{jkp}	duration of reclaiming coal from stockpile j if it starts at point p
F_{ip}	any continuous variable (NLP literature study)
$Fmax_i$	upper limit for the continuous variable F_{ip} (NLP literature study)
$Fmin_i$	lower limit for the continuous variable F_{ip} (NLP literature study)
G_{ijp}	any continuous variable (NLP literature study)
$Gmax_{ij}$	upper limit for the continuous variable G_{ijp} (NLP literature study)
$Gmin_{ij}$	lower limit for the continuous variable G_{ijp} (NLP literature study)
H	scheduling time horizon
i,ii	set of mines
Income	income per kt reclaimed (R/kt)
j	set of stockpiles
m_{ijp}	a continuous variable substituting the bilinear term (NLP literature study)
p	set of event points or time-slots
Q_{ijp}	quantity variable for event i in unit j at point p (SOS1 literature study)
QQ_{jpi}	SOS1 quantity variable for event i in unit j at point p (SOS1 literature study)
q_b_{ijp}	amount of coal conveyed from mine i to stockpile j at point p
q_r_{ijp}	amount of coal from mine i reclaimed from stockpile j at point p
q_supply_{ipj}	SOS1 variable: amount of coal supplied from mine i at point p to the set of stockpiles j
q_stack_{jpi}	SOS1 variable: amount of coal stacked on stockpile j at point p from the set of mines i
$Rate\_b_i$	rate for conveying coal from mine i
$Rate\_r_j$	rate for reclaiming coal from stockpile j
$Ratio1_{i,ii,j,p}$	variable to substitute the bilinear terms in NLP linearization
$Ratio2_{ii,i,j,p}$	variable to substitute the bilinear terms in NLP linearization
ST_s_{ijp}	amount of coal from mine i on stockpile j at point p

NOMENCLATURE (CONTINUE)

$ST0\_s_{ij}$	starting level of mine i contribution to stockpile j
T_p	time value of a global event point at point p
T_k	time value of a global event point at point k (literature study)
Tf_b_{ijp}	time value if conveying coal from mine i to stockpile j *stops* at point p
Tf_r_{jkp}	time value if reclaiming coal from stockpile j *stops* at point p
Ts_b_{ijp}	time value if conveying coal from mine i to stockpile j *starts* at point p
Ts_r_{jkp}	time value if reclaiming coal from stockpile j *starts* at point p
w_{ijp}	binary variable indicating that coal is conveyed from mine i to stockpile j at point p
w_{ijkl}	four index binary variable to assign stage l of order i to slot k of unit j (literature study)
W_{ip}	binary variable indicating task i to be done at point p
x_{jp}	binary variable indicating that coal is reclaimed from stockpile j at point p
X_{ijp}	binary variable indicating task i to be done in unit j at point p (literature study)
$X_{ijkk'}$	binary variable to indicate the task i starting in unit j at time T_k and ending at $T_{k'}$ (literature study)
Y_{jp}	binary variable indicating unit j to be used at point p
y_{jp}	binary variable indicating stacking coal on stockpile j at p
z_{max}	objective function variable to maximise profit

CHAPTER 3:

Bunk_min	the minimum level of any bunker
Cap_b_i	capacity of bunker i
Cap_strat_j	capacity of strategic stockpile j
CL_sl	limit for strategic stockpile coal contribution to the total amount of coal supplied to the factory at any point p
CL_i	limits for source i contribution to the total feed to the factory at any point
Cost	the handling cost when throwing out and loading back coal at the bunkers or the strategic stockpiles
CT_b_{ij}	change-over time lost when starting extraction from bunker i to stockpile j
$CT\_r_{k,kk}$	change-over time lost when changing the reclaimer position from stockpile k to kk, given there are no stockpiles between k and kk
$CT\_s_{k,kk}$	change-over time lost when changing the stacker position from stockpile k to kk
Dem_e	coal demand of Eastern factory during time horizon
Dem_w	coal demand of Western factory during time horizon

NOMENCLATURE (CONTINUE)

Dur_b_{ijp}	duration of extracting coal from bunker i to yard j if it starts at point p
Dur_bl_{ip}	duration of loading back coal at bunker i if it starts at point p
Dur_min	the minimum duration when coal is extracted from a bunker
Dur_m_{ip}	duration of source i production if production starts at point p
Dur_r_{jkp}	duration of reclaiming coal from stockpile k, yard j if it starts at point p
Dur_s_{jkp}	duration of stacking coal on stockpile k, yard j if it starts at point p
Dur_sl_{jkp}	duration of loading back coal from strategic stockpile j to specific stockpile k, if it starts at point p
H	scheduling time horizon
H_m_r	end-of-period time value for each period r
$heap0\_s_{jk}$	starting heap length of stockpile k on yard j
$heapl\_s_{jkp}$	heap length of stockpile k, yard j, at point p
HH	a big value
i, ii	set of sources
Income_r	income per ton reclaimed
Income_s	income per ton stacked
j, jj	set of stockpile yards
k, kk	set of individual stockpiles per yard
Loaders	the number of front-end loaders available for loading back coal at the bunkers and the strategic stockpiles
$Max0\_s_{jk}$	the maximum capacity of a stockpile k on yard j
Min_length	the minimum length for any individual stockpile k
Out_b_{ip}	amount of coal outside bunker i at point p
$Out0\_b_i$	starting level of coal outside bunker i
p	set of event points
per_{rp}	subset to assign event points to periods
Pos_r_{jkp}	reclaimer position tracking variable for stockpile k, yard j, point p
$Pos0\_r_{jk}$	starting reclaiming position on stockpile k, yard j
$Pos0\_s_{jk}$	starting stacker position on stockpile k, yard j
Prop_penalty	penalty when coal is bypassed directly to the factory
q_b_{ijp}	amount of coal extracted from bunker i to yard j, point p
q_bl_{ip}	amount of coal loaded back at bunker i at point p
q_bo_{ip}	amount of coal thrown out at bunker i at point p

NOMENCLATURE (CONTINUE)

q_m_{ip}	amount of coal produced by source i at point p
q_prop_{ijp}	amount of coal from source i bypassed at yard j, point p
q_r_{ijkp}	amount of coal from source i reclaimed from yard j, stockpile k at point p
q_rsl_{jkp}	amount of coal from strategic stockpile j that were loaded back to stockpile k and reclaimed at point p
q_s_{ijkp}	amount of coal from source i stacked on yard j, stockpile k at point p
q_sl_{jkp}	amount of coal loaded back from strategic stockpile j to stockpile k at point p
q_so_{jp}	amount of coal thrown out at strategic stockpile j at point p
r	set of time periods
$Rate\_b_j$	maximum rate for conveying coal from bunker i
$Rate\_bl$	rate for loading back coal with one front-end loader at the bunkers or the strategic stockpiles
$Rate\_f$	the maximum rate at which one side of the factory can receive coal
$Rate\_m_{ir}$	production rate of source i in period r
$Rate\_r$	the maximum rate at which any reclaimer can reclaim
$Rate\_s$	the maximum rate at which any stacker can stack
ST_b_{ip}	amount of coal stored in bunker i at point p
ST_sl_{jkp}	amount of strategic stockpile coal on stockpile k, yard j, at point p
ST_sm_{ijkp}	amount of coal from source i on stockpile k, yard j, at point p
$ST0\_b_i$	starting level of bunker i
$ST0\_sl_{jk}$	starting level of coal from strategic stockpile j on stockpile k
$ST0\_sm_{ijk}$	starting level of source i contribution to stockpile k on yard j
$Strat0_j$	starting level of strategic stockpile j
$Strat_{jp}$	amount of coal on strategic stockpile j at point p
Tf_b_{ijp}	finishing time value if extracting coal from bunker i to yard j *stops* at point p
Tf_bl_{ip}	finishing time value if loading back coal at bunker i *stops* at point p
Tf_m_{ip}	finishing time value if source i production *stops* at point p
Tf_r_{jkp}	finishing time value if reclaiming coal from stockpile k, yard j *stops* at point p
Tf_s_{jkp}	finishing time value if stacking coal from source i on stockpile k, yard j *stops* at point p
Tf_sl_{jp}	finishing time value if loading back coal from strategic stockpile j *stops* at point p
Tot_length	total length of any yard j
$Total\_e_p$	total feed to the Eastern factory at point p
$Total\_w_p$	total feed to the Western factory at point p

NOMENCLATURE (CONTINUE)

Ts_b_{ijp}	starting time value if extracting coal from bunker i to yard j *starts* at point p
Ts_bl_{ip}	starting time value if loading back coal at bunker i *starts* at point p
Ts_m_{ip}	starting time value if source i production *starts* at point p
Ts_r_{jkp}	starting time value if reclaiming coal from stockpile k, yard j *starts* at point p
Ts_s_{jkp}	starting time value if stacking coal from source i on stockpile k, yard j *starts* at point p
Ts_sl_{jp}	starting time value if loading back coal from strategic stockpile j *starts* at point p
$Ts0\_m_r$	starting time value for each period r
$v1_{ip}$	binary variable indicating that coal is thrown out at bunker i at point p
$v2_{ip}$	binary variable indicating that coal is loaded back into bunker i at point p
w_{ijp}	binary variable indicating that coal is conveyed from mine i to stockpile j at point p
ww_{jkp}	binary variable indicating coal is stacked on yard j, stockpile k at point p
$x2_{ijp}$	binary variable indicating that coal is bypassed from mine i to yard j, at point p
x_{jkp}	binary variable indicating coal is reclaimed from yard j, stockpile k at point p
y_{jkp}	binary variable indicating a new stockpile is created on position k, yard j, at point p
$z1_{jp}$	binary variable indicating that coal is thrown out at strategic stockpile j at point p
$z2_{jp}$	binary variable indicating that coal is loaded back from strategic stockpile j at point p
z_{max}	objective function variable to maximise profit

CHAPTER 4:

a	set of options for coal extracted from the bunker
b	set of options for coal conveyed to the stacker
$BBleedin\_e_p$	the variable to substitute the non-linear part in the Eastern blend equation during linearization, represents the blend of the coal loaded back from the strategic stockpiles at a specific point p
$BBleedin\_w_p$	the variable to substitute the non-linear part in the Western blend equation during linearization, represents the blend percentage of the coal loaded back from the strategic stockpiles at a specific point p
$BBlend\_e_{ip}$	the variable to substitute the non-linear part in the Eastern blend equation during linearization, represents the blend percentage of a specific mine i's coal at a specific point p
$BBlend\_w_{ip}$	the variable to substitute the non-linear part in the Western blend equation during linearization, represents the blend percentage of a specific mine i's coal at a specific point p

NOMENCLATURE (CONTINUE)

$Bleedin\_e_p$	the percentage contribution of coal loaded back from the strategic stockpile in the total amount of coal supplied to the Eastern factory at point p
$Bleedin\_w_p$	the percentage contribution of coal loaded back from the strategic stockpile in the total amount of coal supplied to the Western factory at point p
$Blend\_e_{ip}$	the percentage contribution of mine i's coal in the total amount of coal supplied to the Eastern factory at point p
$Blend\_w_{ip}$	the percentage contribution of mine i's coal in the total amount of coal supplied to the Western factory at point p
Bunk_min	the minimum level of any bunker
c	set of options for produced coal at the bunker
Cap_b_i	capacity of bunker i
CL_bleedin	limit for strategic stockpile coal contribution to the total amount of coal supplied to the factory at any point p
CL_e_i	blend plan contribution percentage of mine i coal supplied to the Eastern factory
CL_w_i	blend plan contribution percentage of mine i coal supplied to the Western factory
Cle_bleedin	blend plan contribution percentage of strategic stockpile coal supplied to the Eastern factory
CL_i	limits for source i contribution to the total feed to the factory at any point
CLw_bleedin	blend plan contribution percentage of strategic stockpile coal supplied to the Western factory
CT_b_{ij}	change-over time lost when starting extraction from bunker i to stockpile j
$CT\_r_{k,kk}$	change-over time lost when changing the reclaimer position from stockpile k to kk, given there are no stockpiles between k and kk
d	set of options for coal handling outside a bunker or a strategic stockpile
Dur_bl_{ip}	duration of loading back coal at bunker i if it starts at point p
Dur_min	the minimum duration when coal is extracted from a bunker
Dur_m_{ip}	duration of source i production if production starts at point p
Dur_prop_{ijp}	duration of the bypass event from mine i to yard j, starting at point p
Dur_r_{jkp}	duration of reclaiming coal from stockpile k, yard j if it starts at point p
Dur_r_{jpf}	SOS1 variable to indicate the duration of either an operational event or a maintenance event (set f) at reclaimer j, point p
Dur_rmaint_{jr}	required reclaimer j maintenance during period r
Dur_s_{jpf}	SOS1 variable to indicate the duration of either an operational event or a maintenance

NOMENCLATURE (CONTINUE)

	event (set f) at stacker j, point p
Dur_smaint_{jr}	required stacker j maintenance during period r
f	set of equipment availability options
H	scheduling time horizon
HH	a big value
i, ii	set of sources
ie_i	set of Eastern sources (subset of sources i)
iw_i	set of Western sources (subset of sources i)
j, jj	set of stockpile yards
k, kk	set of individual stockpiles per yard
$Loaders$	the number of front-end loaders available for loading back coal at the bunkers and the strategic stockpiles
$Max0\_s_{jk}$	the maximum capacity of a stockpile k on yard j
Out_b_{ip}	amount of coal outside bunker i at point p
$Portion1_{ijkp}$	the variable to substitute the non-linear part in the reclaiming process equation during linearization, represents the layers of a specific mine i's coal
$Portion2_{jkp}$	the variable to substitute the non-linear part in the reclaiming process equation during linearization, represents the layers of coal loaded back from the strategic stockpile
Pos_r_{jkp}	reclaimer position tracking variable for stockpile k, yard j,at point p
$Pos0\_r_{jk}$	starting reclaiming position on stockpile k on yard j
q_bfel_{ipd}	SOS1 variable to ensure that the front-end loaders are used for only one of the handling options d at bunker i, point p
q_b_{ipj}	SOS1 variable for the amount of coal extracted from bunker i to stockpile yard j at point p, where set j is controlled
q_bopt_{ijpa}	SOS1 variable to ensure that only one of the options a is chosen for the stream of coal extracted from bunker i to stockpile yard j at point p
$q\_e2w_{p\ ie}$	SOS1 variable for the total amount of coal conveyed from the Eastern mines ie to the Western stockpiles at point p, where set ie is controlled
q_m_{ip}	amount of coal produced by source i at point p
q_mopt_{ipc}	SOS1 variable to ensure that only one option c is activated for mine i's production at point p
q_prop_{jpi}	SOS1 variable for the amount of coal bypassed at stockpile yard j from bunker i to at point p, where set j is controlled

NOMENCLATURE (CONTINUE)

q_r_{ijkp}	amount of coal from source i reclaimed from stockpile k, yard j at point p
q_rsl_{jkp}	amount of coal from strategic stockpile j that were loaded back to stockpile k and reclaimed at point p
q_s_{ijkp}	amount of coal from source i stacked on stockpile k, yard j at point p
q_sl_{jkp}	amount of coal loaded back from strategic stockpile j to stockpile k at point p
q_sopt_{jpb}	SOS1 variable to ensure that only one of the options b is chosen for the type of coal conveyed to stacker j at point p
q_supply_{jpi}	SOS1 variable for the amount of coal supplied to stacker j from bunker i to at point p, where set i is controlled
$q\_w2e_{p\ iw}$	SOS1 variable for the total amount of coal conveyed from the Western mines iw to the Eastern stockpiles at point p, where set iw is controlled
QQ_{jpi}	SOS1 quantity variable for event i in unit j at point p (literature study)
$Rate\_b_{j}$	maximum rate for conveying coal from bunker i
Rate_bl	rate for loading back coal with one front-end loader at the bunkers or the strategic stockpiles
Rate_f	the maximum rate at which one side of the factory can receive coal
$Rate\_m_{ir}$	production rate of source i in period r
Rate_r	the maximum rate at which any reclaimer can reclaim
Rate_s	the maximum rate at which any stacker can stack
$Ratio_{jkp}$	the ratio in which the layers on the stockpile is reclaimed during the reclaiming process
ST_b_{ip}	amount of coal stored in bunker i at point p
ST_sl_{jkp}	amount of strategic stockpile coal on stockpile k, yard j, at point p
ST_sm_{ijkp}	amount of coal from source i on stockpile k, yard j, at point p
$Strat_{jp}$	amount of coal on strategic stockpile j at point p
Tf_b_{ijp}	finishing time value if extracting coal from bunker i to yard j *stops* at point p
Tf_bl_{ip}	finishing time value if loading back coal at bunker i *stops* at point p
Tf_m_{ip}	finishing time value if source i production *stops* at point p
Tf_prop_{ijp}	finish time value if coal is bypassed to the factory from mine i at yard j, starting at point (p-1)
Tf_r_{jp}	finishing time value for any reclaiming event on yard j that started at the previous point (p-1)
Tf_s_{jp}	finishing time value for any event involving the stacker on yard j at the previous point (p-1)

NOMENCLATURE (CONTINUE)

Tot_length	total length of any yard j
$Total\_w_p$	total feed to the Western factory at point p
Ts_bl_{ip}	starting time value if loading back coal at bunker i *starts* at point p
Ts_m_{ip}	starting time value if source i production *starts* at point p
Ts_re_p	starting time value for any reclaiming or bypassing event on the Eastern side at point p
Ts_rw_p	starting time value for any reclaiming or bypassing event on the Western side at point p
Ts_s_{jp}	starting time value for any event involving the stacker on yard j at point p
ww_{jkp}	binary variable indicating coal is stacked on yard j, stockpile k at point p
$x2_{ijp}$	binary variable indicating coal is bypassed from mine i to yard j, at point p
x_{jkp}	binary variable indicating coal is reclaimed from yard j, stockpile k at point p
z_{max}	objective function variable to be maximised