Identifying Optimal Mining Sequences for Continuous Miners

Dr. Joseph C. Hirschi
Project Manager
Illinois Clean Coal Institute

Presentation Outline

- **Background and Current Practice**
- **Need for Optimization Tool**
- **Dynamic Programming**
- **Dynamic Programming Algorithm**
- **Application Case Study**
- **Acknowledgements**

Background and Current Practice

SSP Model

Input Section

- Equipment Characteristics
  - Operating rates
  - Capacities
- Human Resource Data
  - Shift schedule
  - Staffing levels
- Geologic Data
  - Seam height
  - Material densities
- Geometric Data
  - Haulage routes
  - Cut sequence

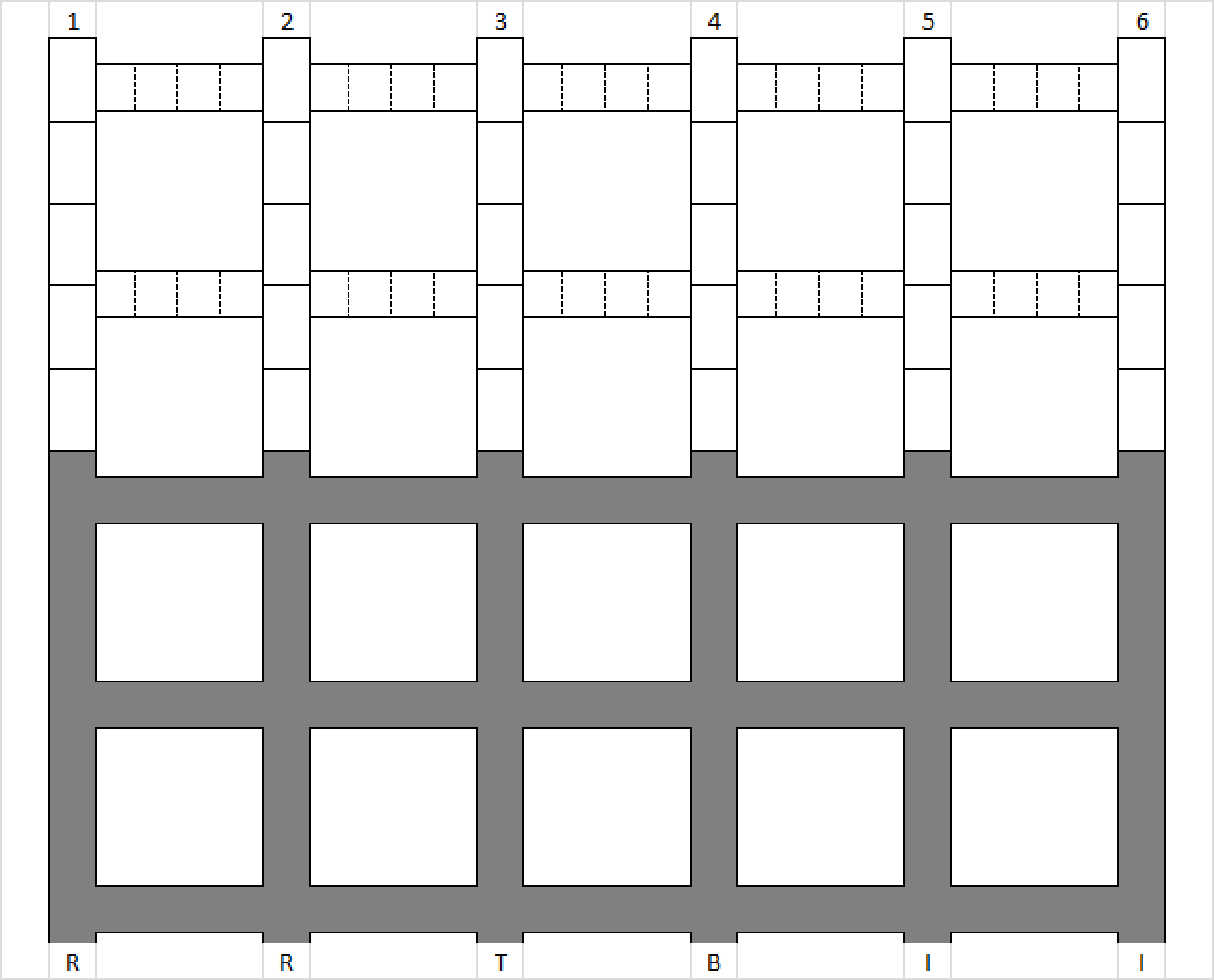
Computing Section

- Loading Rate
- Incremental Delays
  - Change-out time/cut
  - Wait on car/cut

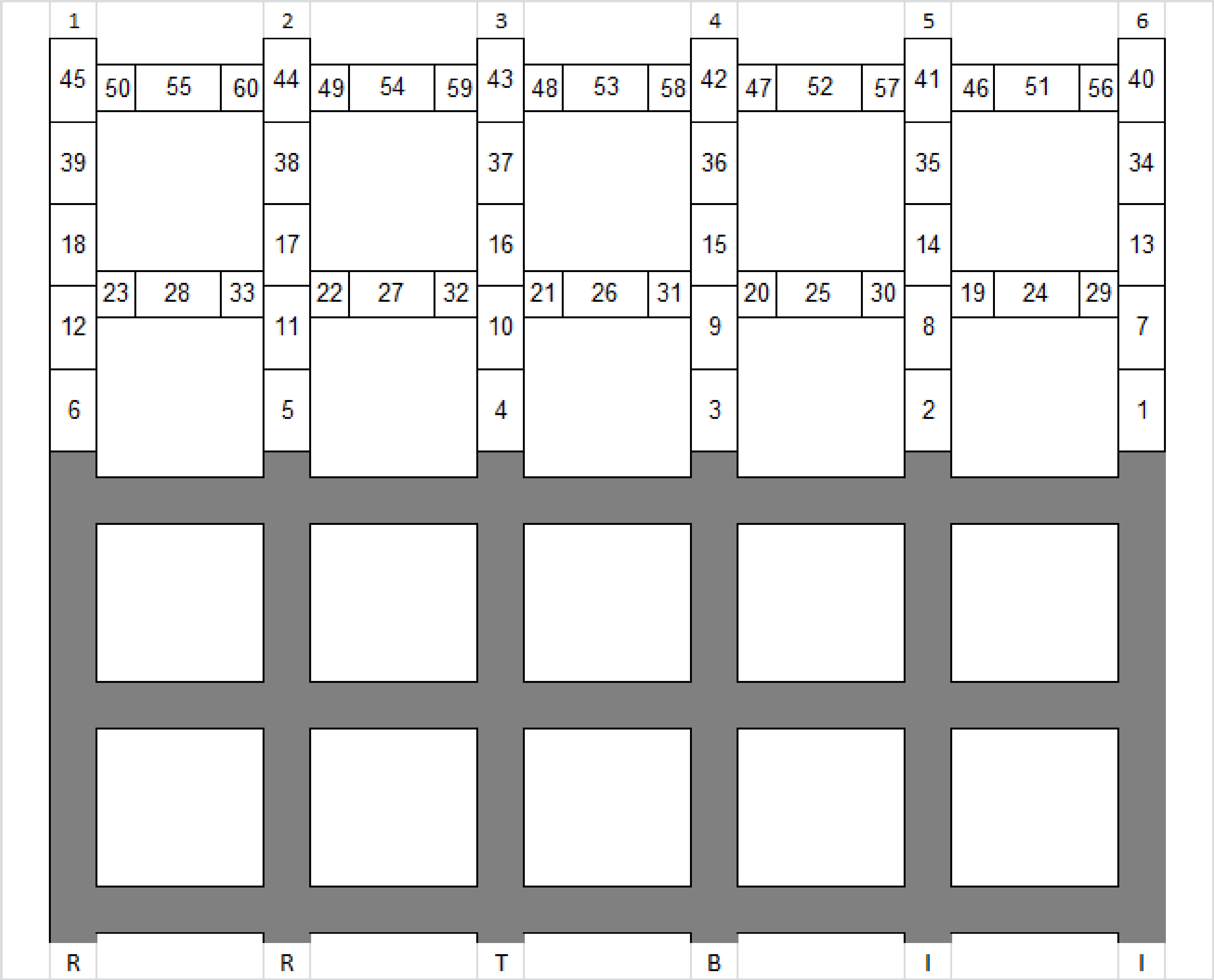
Output Section

- Cycle Times
  - Loading
  - Change-out
  - Wait on car
  - Tram
- Delays
- Production
  - Tons
  - Feet of advance
- Mining Rates

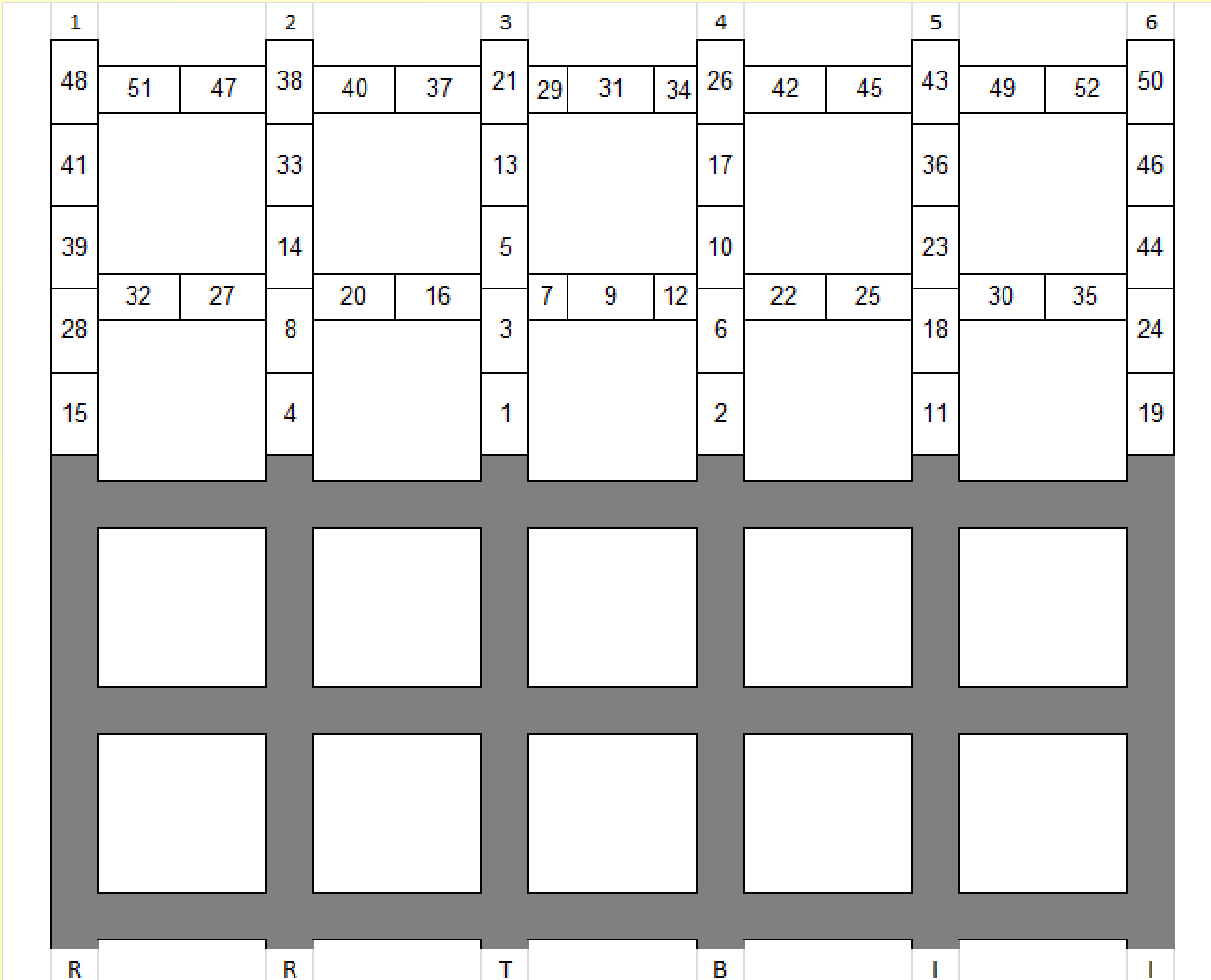
Background and Current Practice



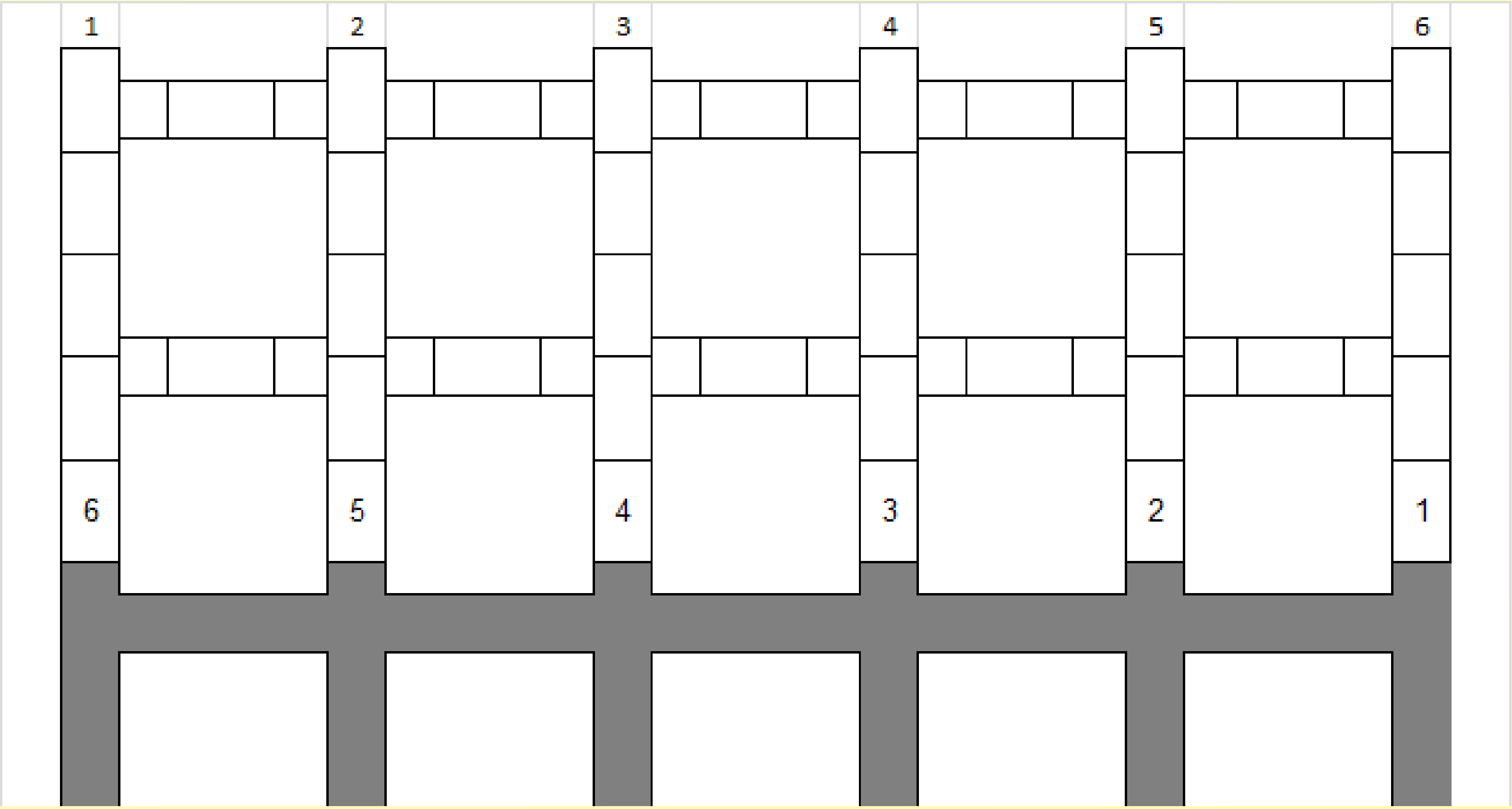
Background and Current Practice



Background and Current Practice

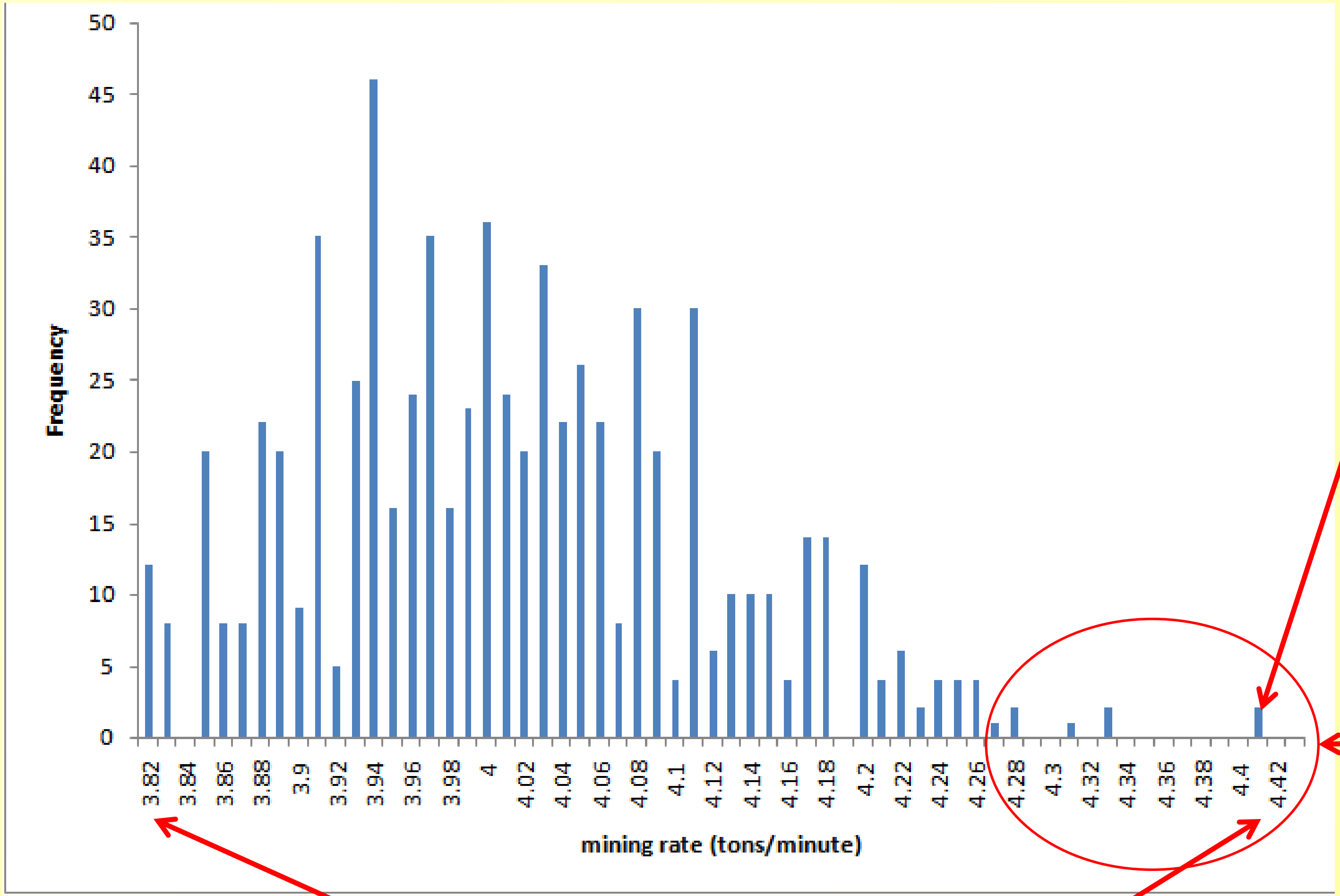


Need for Optimization Tool



720 different sequences

Need for Optimization Tool



2 of 720 are optimal

8 of 720 (only 1%) are in the top 25% of the productivity range

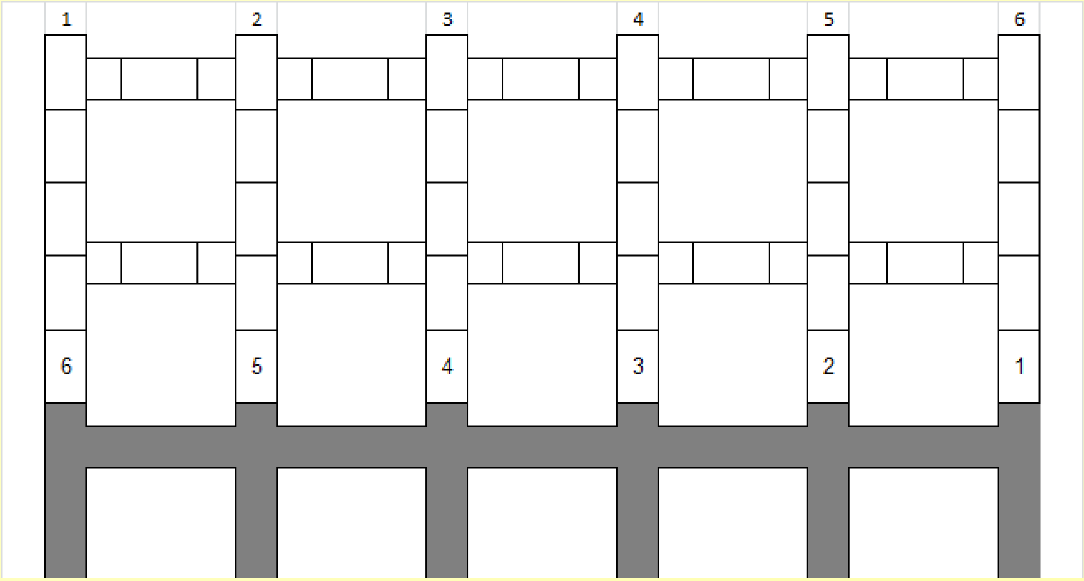
15% improvement between best case and worst case

Dynamic Programming

- Dynamic programming is a recursive, or step-by-step, approach to solving optimization problems.
- At each step, referred to as a STAGE, parameters and constraints of all FEASIBLE options or STATES are evaluated using an OPTIMAL VALUE FUNCTION.
- This requires the following items to be defined:
  - Stages
  - Feasible states at each stage
  - Optimal value function (OVF)
  - Recurrence relation

Dynamic Programming

- **In room-and-pillar mining:**
  - **Stages are cuts to be mined**



  - **Feasible states at each stage are cuts satisfying boundary conditions and constraints**

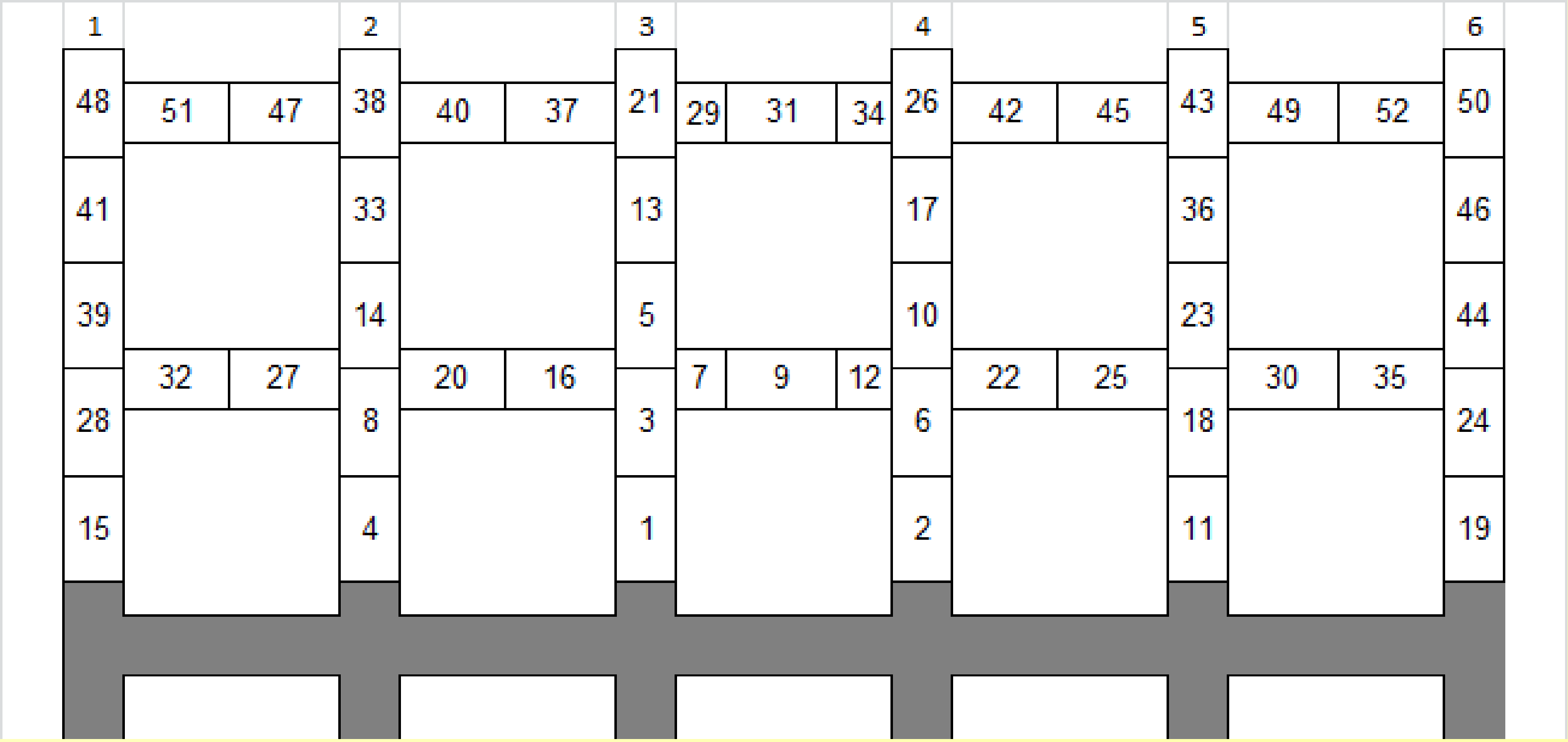
Dynamic Programming

Constraint Matrix

	Bolting	Ventilation
Regulatory	• No travel inby unsupported top • Crosscuts may only be turned out of specified entries • Mined areas must be bolted within specified time	• Time-weighted average dust exposure limits must not be exceeded • Roof bolter can be downwind of CM for only two cuts/shift
Operational	• Maintain a buffer between bolting and mining functions • Mining cannot occur when bolter blocks haulage path	• Start crosscuts head-on and mine in the direction of ventilation airflow whenever possible • Do not mine entry that is deep enough for mining crosscut

Dynamic Programming

Examples of constraints and boundary conditions



- Room-and-pillar mining has obvious geometric constraints, i.e. Cut #5 cannot be mined until Cut #1 and Cut #3 have been mined.
- Safety regulations dictate other clear constraints, i.e. Cut #1 and Cut #3 must also be bolted before Cut #5 can be mined.

Dynamic Programming

- **The optimal value function (OVF) scores feasible states in terms of certain evaluation criteria**
  - **Productivity**
  - **Cycle time**
  - **Dust exposure**

- **The recurrence relation is used to select the feasible state with the maximum or minimum score, depending on the objective function, i.e.**
  - **Maximize production**
  - **Minimize cycle time**
  - **Minimize dust exposure**

Dynamic Programming Algorithm

Overall Methodology:

- **Develop algorithm to quantify the production process**
- **Use algorithm for selection of cuts**

Strategic Planning versus Tactical Planning

Dynamic Programming Algorithm

Guiding Policies and Practices

- **Complete crosscuts in a timely fashion**
- **Maximize starting crosscuts head-on**
- **Mine crosscuts in the direction of ventilation air flow**
- **Maximize double cutting**
- **Maintain buffer between continuous miner and roof bolter**
- **Repeatable sequence for each crosscut of advance**

Dynamic Programming Algorithm

Optimal Value Function

f_i(X) = minimum total CCT_i(X) that results from following an optimal policy for stage *i* given state X

where

CCT_i(X) = cut cycle time for stage *i* given state X

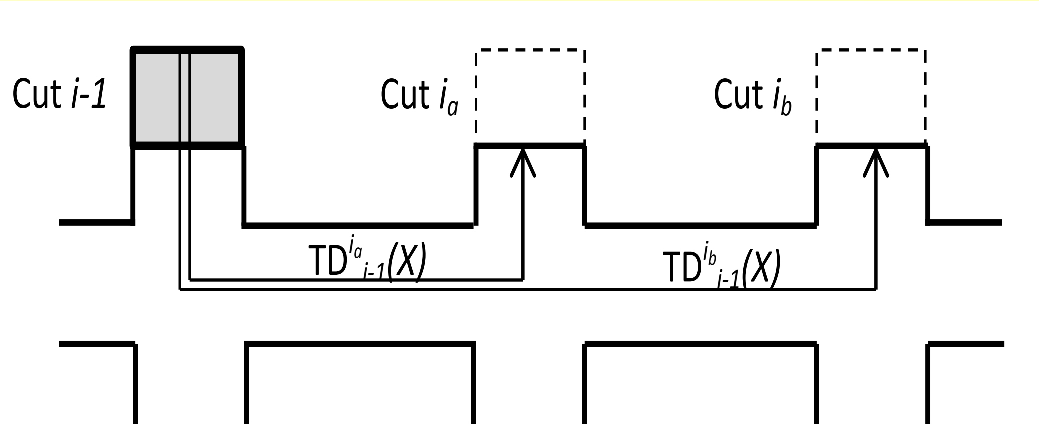
= $MOVE^i_{i-1}$(X) + $PROD_i$(X)

and $MOVE^i_{i-1}$(X) = the place change element of CCT_i(X) from stage *i-1* to stage *i* in state X

$PROD_i$(X) = the production element of CCT_i(X) for stage *i given state X*

Dynamic Programming Algorithm

Place Change Element



Parameters

$TD^{i}_{i-1}(X)$ = tram distance from stage *i-1* to stage *i* given state X
SPD_{CM} = CM tram speed

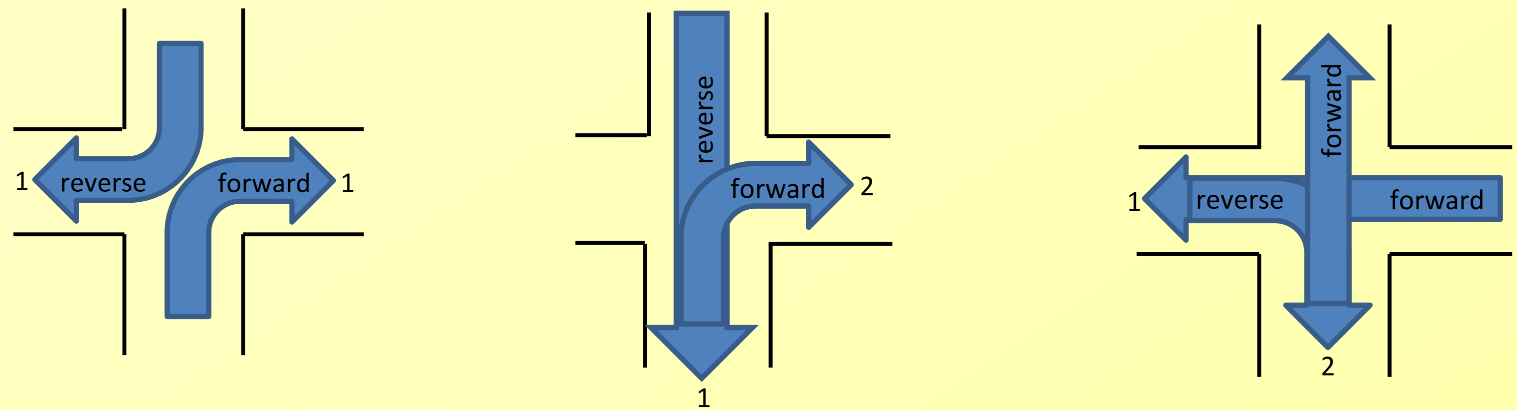
Basic Time Value for Place Change Element

$$TD^{i}_{i-1}(X) \;/\; SPD_{CM}$$

Dynamic Programming Algorithm

Adjustments to Place Change Element Basic Time Value

- **Cornering Adjustment Factor: $TCOR^{i}_{i-1}(X)$**



$$TCOR^{i}_{i-1}(X) = [NUMCOR^{i}_{i-1}(X) * CORTM_{CM}] + [NUMDRCH^{i}_{i-1}(X) * DRCHTM_{CM}]$$

where $NUMCOR^{i}_{i-1}(X)$ = number of corners negotiated moving from stage *i-1* to stage *i* given state X

$CORTM_{CM}$ = extra time required for CM to negotiate a corner

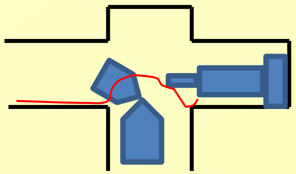
$NUMDRCH^{i}_{i-1}(X)$ = number of times CM reverses direction in negotiating corners while moving from stage *i-1* to stage *i* given state X

$DRCHTM_{CM}$ = extra time required when CM reverses direction

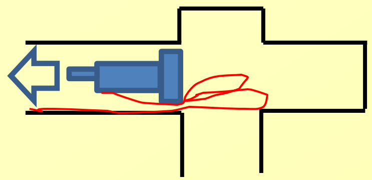
Dynamic Programming Algorithm

Adjustments to Place Change Element Basic Time Value

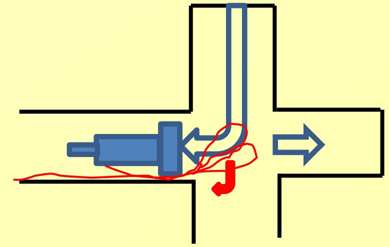
- **Cable Handling Adjustment Factor: $CH^{i}_{i-1}(X)$**



$HANGTM_{CM}$



$HOOKTM_{CM}$



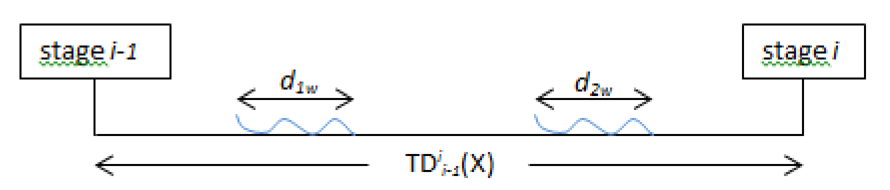
$HANDTM_{CM}$

$$
\begin{aligned}
CH^{i}_{i-1}(X) \quad = \quad & [NUMHANG^{i}_{i-1}(X) * HANGTM_{CM}] \\
& + [NUMHOOK^{i}_{i-1}(X) * HOOKTM_{CM}] \\
& + [NUMHAND^{i}_{i-1}(X) * HANDTM_{CM}]
\end{aligned}
$$

Dynamic Programming Algorithm

Adjustments to Place Change Element Basic Time Value

- **Road Condition Adjustment Factor: $RDCON^{i}_{i-1}(X)$**
  - **Water**
  - **Soft roads**
  - **Bad top**



$(d_{1w} + d_{2w}) = WATER^{i}_{i-1}(X)$

$$RDCON^{i}_{i-1}(X) = [WATER^{i}_{i-1}(X) / WATERSPD_{CM}] - [WATER^{i}_{i-1}(X) / SPD_{CM}] + [SOFTBT^{i}_{i-1}(X) / SOFTBTSPD_{CM}] - [SOFTBT^{i}_{i-1}(X) / SPD_{CM}] + [BDTOP^{i}_{i-1}(X) / BDTOPSPD_{CM}] - [BDTOP^{i}_{i-1}(X) / SPD_{CM}]$$

Dynamic Programming Algorithm

Production Element

2 Components

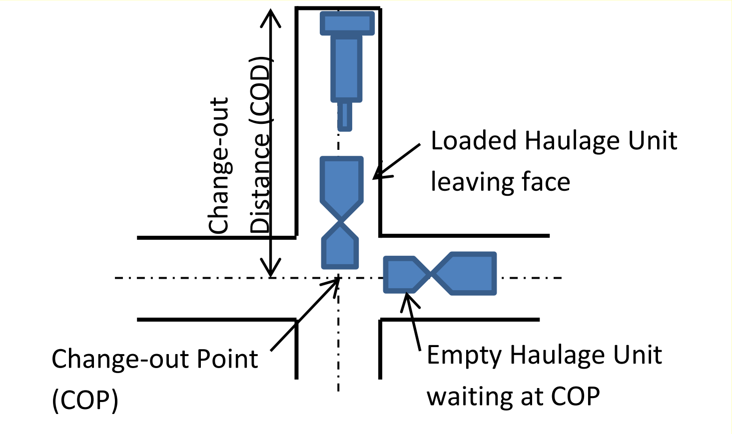
- **$COT_i(X)$ = change out time for stage *i* given state X**
- **$LT_i(X)$ = loading time for stage *i* given state X**

Basic Time Value for Production Element

$$PROD_i(X) = COT_i(X) + LT_i(X)$$

Dynamic Programming Algorithm

Production Element – Change-out Time Component



Parameters

$COD_i(X)$ = change-out distance for stage *i* given state X
SPD_{HU} = haulage unit tram speed
$TRIPS_i(X)$ = ROUNDUP [$CUTVOL_i(X)$ / (PLD_{HU} * FILL)]
SWIN = haulage unit turn-around (switch in) time at COP

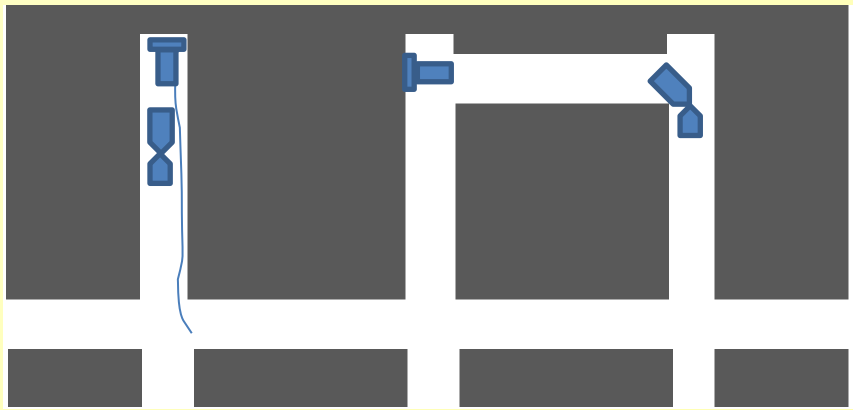
Basic Time Value for Change-out Time Component

$$COT_i(X) = \{[2*COD_i(X)/SPD_{HU}]+SWIN\} * TRIPS_i(X)$$

Dynamic Programming Algorithm

Adjustments to Production Element Change-out Time Component

- **Change-out Condition Adjustment Factor: $COCON_i(X)$**



$COCON_i(X)$ = 1.0 if CO path is unobstructed by hanging line curtain, corners that must be negotiated, and/or poor road conditions
= 1.5 if CO path is obstructed by one of the above conditions
= 2.0 if CO path is obstructed by two of the above conditions

$$COT_i(X) = \{\{2*COD_i(X)/[SPD_{HU} / COCON_i(X)]\}+SWIN\} * TRIPS_i(X)$$

Dynamic Programming Algorithm

Adjustments to Production Element Change-out Time Component

- **Wait-on-Car Adjustment Factor: $WOC_i(X)$**

$$WOC_i(X)=\{(2/SPD_{HU})*\{HD - [NCARS_i(X)-1]*COD_i(X)\} + \{PLD/DR_{HU}*[3 - 2*NCARS_i(X)]\} + \{SWIN*[2 - NCARS_i(X)]\}\} *\mathbf{TRUNC}(TRIPS/NCARS)$$

$$\mathbf{COT_i(X) = \{\{\{2*COD_i(X)/[SPD_{HU}/COCON_i(X)]\}+SWIN\}*TRIPS_i(X)\}+WOC_i(X)}$$

Dynamic Programming Algorithm

Production Element – Loading Time Component

Parameters

$CUTVOL_i(X)$ = volume of coal in stage *i* given state X
= $DEPTH_i(X)$ * $WIDTH_i(X)$ * $HEIGHT_i(X)$ * RCDEN

$WIDTH_i(X)$*$HEIGHT_i(X)$*RCDEN = constant
= tons/foot of advance (TFA)

LR_{CM} = CM loading rate

Basic Time Value for Loading Time Component

$$LT_i(X) = \{[TFA * DEPTH_i(X)] / LR_{CM}\}$$

Dynamic Programming Algorithm

Adjustment to Production Element Loading Time Component

- **Clean-up Adjustment Factor: $WOC_i(X)$**

$RESET_{HU}$ = haulage unit reset during cleanup passes

$$LT_i(X) = \{[TFA * DEPTH_i(X)] / LR_{CM}\} + RESET_{HU}$$

Application Case Study

Constraint Matrix

	Bolting	Ventilation
Regulatory	• No travel inby unsupported top • Turn crosscuts only out of #3, #4, #8, and #9 Entries • Mined areas must be bolted within specified time	• Time-weighted average dust exposure limits must not be exceeded • Roof bolter can be downwind of CM for only two cuts/shift
Operational	• Maintain a buffer between bolting and mining functions • Mining cannot occur when bolter blocks haulage path	• Start crosscuts head-on and mine in the direction of ventilation airflow whenever possible • Do not mine entry that is deep enough for mining crosscut

Application Case Study

Iterations

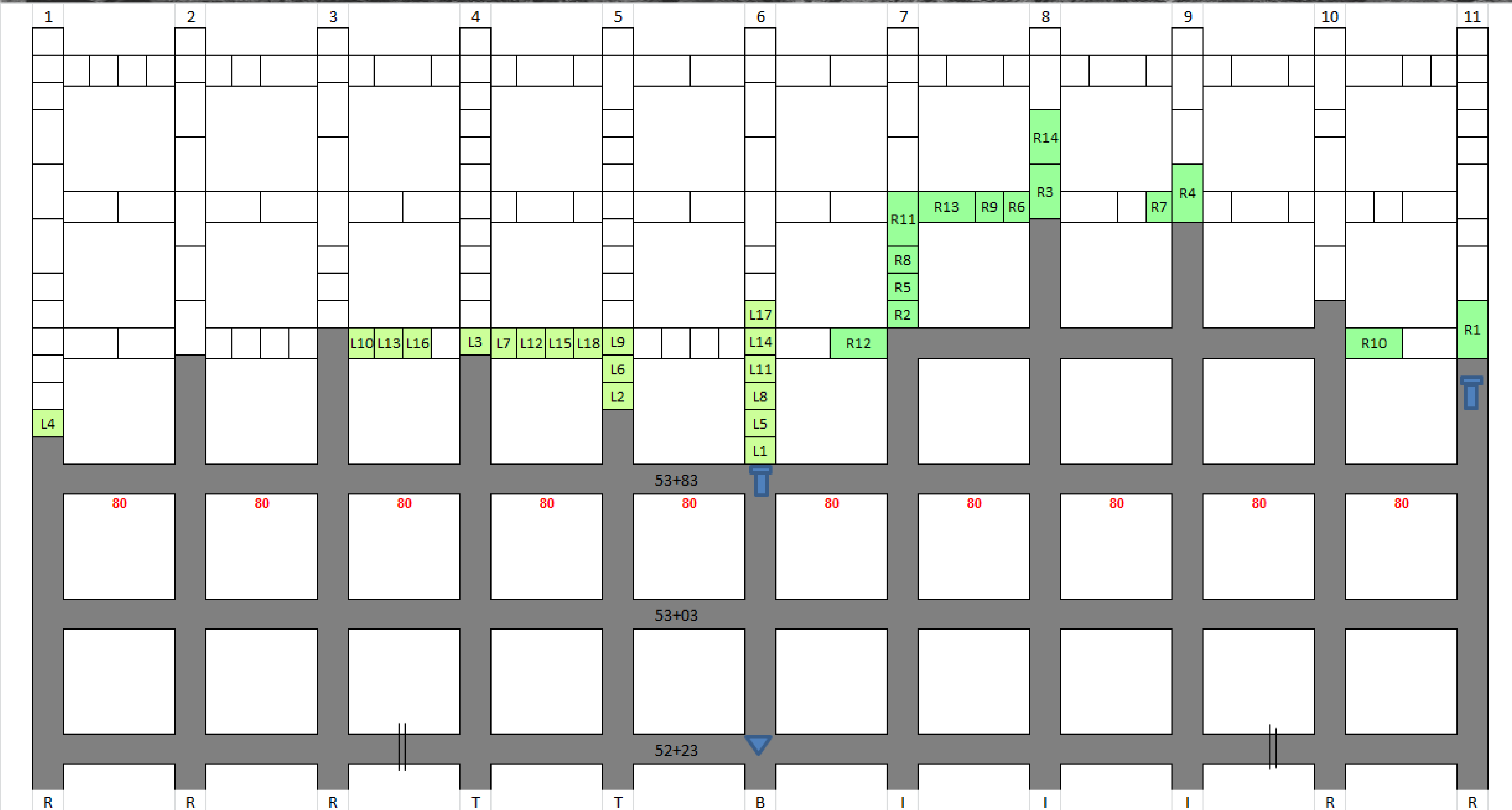
	#1 Entry	#2 Entry	#3 Entry		#4 Entry		#5 Entry	#6 Entry
Cuts Available for 4th Cut	E1.1	E2.1	E3.1	C34.1	E4.2	C45.1	E5.2	E6.2
Constraint - bolt, vent, both			vent		both	bolt	bolt	
Corner/Curtain Factor	1	1.5		1.5				1.5
HD	480	480		400				240
COD	99	84		89				104
WOC Factor	0.84	3.04		-0.10				-2.99
DEPTH	10	30		20				10
OSD	30	6		6				18
TRIPS - number of loads	10	21		14				9
CO Segment	7.87	20.69		12.30				8.94
Loading Segment	9.50	18.62		19.13				8.31
Production Element	17.37	39.31		31.43				17.25
Number of Corners	2	2		3				2
Direction Changes	1	1		1				1
Cable Hook-ons	4	4		3				3
Cable Handling	0	0		0				2
TD	345	330		255				270
Place Change Element	8.21	8.01		7.44				10.99
DP Model CCT Value	25.58	47.32		38.87				28.24

Application Case Study

Recursive Paths

Path										
1st Cut Options					E6.1					
Optimal value CCT$_i$(X)					16.53					
2nd Cut Options		E4.1						E5.1		
Optimal value CCT$_i$(X)		28.99						28.65		
f_i(X)		45.51						45.18		
3rd Cut Options	E1.1		E5.1					E4.1		
Optimal value CCT$_i$(X)	28.55		29.49					26.18		
f_i(X)	74.07		75.00					71.36		
4th Cut Options	E6.2		E6.2			E1.1				E6.2
Optimal value CCT$_i$(X)	26.05		26.81			28.55				28.24
f_i(X)	100.12		101.81			99.91				99.60
5th Cut Options	E5.1		E1.1		E5.2		E6.2			E5.2
Optimal value CCT$_i$(X)	28.79		32.44		26.40		26.05			21.99
f_i(X)	128.91		134.25		126.31		125.96			121.59
6th Cut Options	C45.1		E5.2		E6.2		E5.2			E1.1
Optimal value CCT$_i$(X)	32.46		26.40		26.94		20.59			29.63
f_i(X)	161.36		160.65		153.26		146.55			151.22
7th Cut Options	E6.3		C45.1		C45.1		C45.1			E6.3
Optimal value CCT$_i$(X)	36.70		32.59		35.40		32.59			33.47
f_i(X)	198.07		193.25		188.66		179.14			184.68
8th Cut Options	E5.2		E6.3		E5.3		E6.3			C45.1
Optimal value CCT$_i$(X)	22.83		36.70		39.01		36.70			35.65
f_i(X)	220.90		229.95		227.67		215.85			220.33
9th Cut Options	C34.1		E5.3		E6.3		E5.3			E5.3
Optimal value CCT$_i$(X)	43.06		37.71		34.63		37.71			39.01
f_i(X)	263.95		267.67		262.29		253.56			259.34
10th Cut Options	E6.4		C34.1		C34.1		C34.1			E6.4
Optimal value CCT$_i$(X)	32.79		43.32		46.11		43.32			29.29
f_i(X)	296.74		310.99		308.40		296.88			288.62
11th Cut Options	E5.3		E6.4	E1.2		C45.2	E6.4			C34.1
Optimal value CCT$_i$(X)	37.88		32.79	49.39		49.69	32.79			46.27
f_i(X)	334.62		343.78	357.79		358.09	329.68			334.89
12th Cut Options	E1.2	C45.2	C45.2	E6.4		E6.4	C45.2		C45.2	E1.2
Optimal value CCT$_i$(X)	46.06	46.77	49.72	28.39		26.10	49.72		49.69	49.39
f_i(X)	380.67	381.39	393.50	386.18		384.19	379.39		384.58	384.28
13th Cut Options							C34.2			
Optimal value CCT$_i$(X)							49.36			
f_i(X)							428.75			
14th Cut Options							E6.5			
Optimal value CCT$_i$(X)							32.60			
f_i(X)							461.35			
15th Cut Options							C45.3			
Optimal value CCT$_i$(X)							52.88			
f_i(X)							514.24			

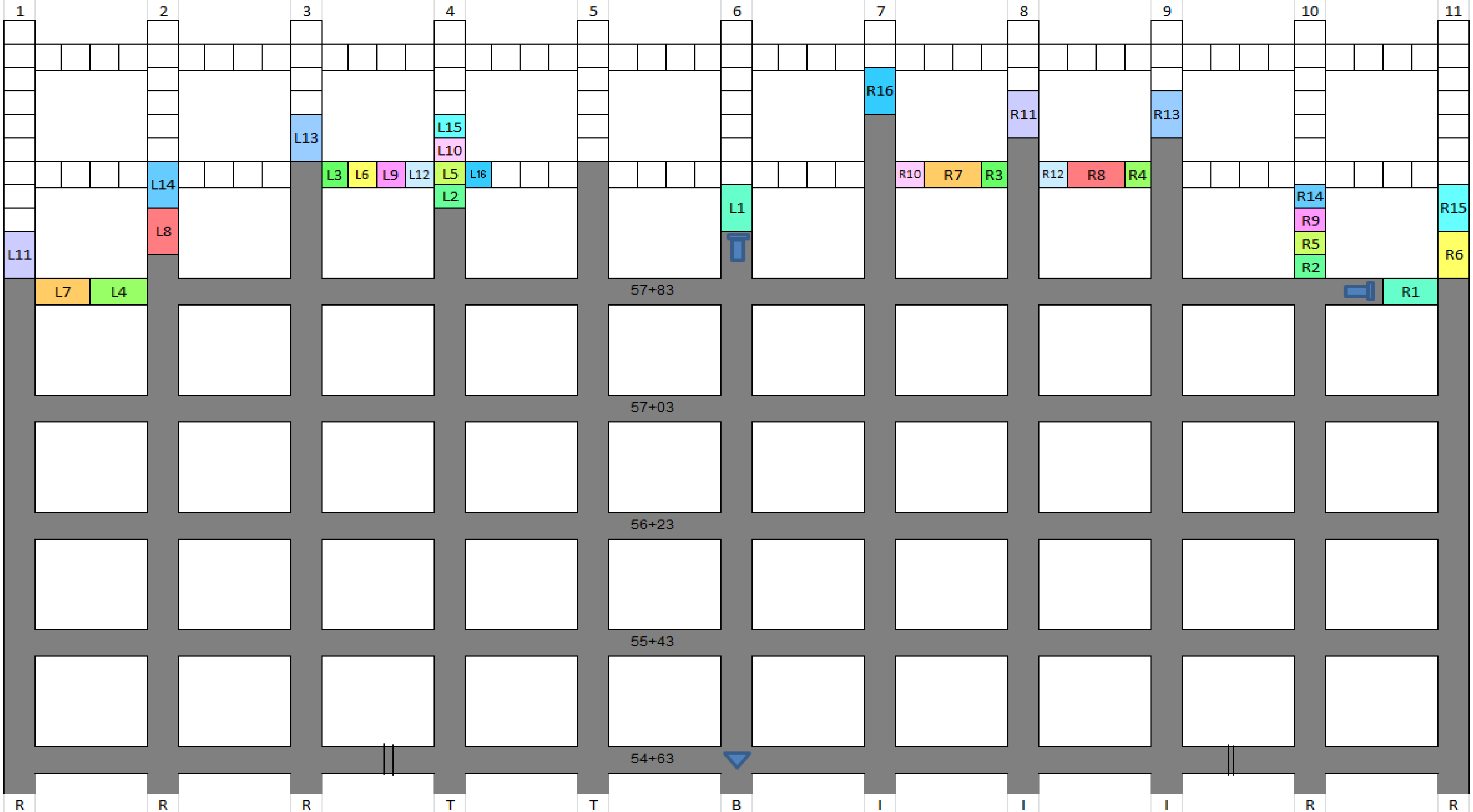
Application Case Study



Predicted Optimal Mining Sequence for Day 1

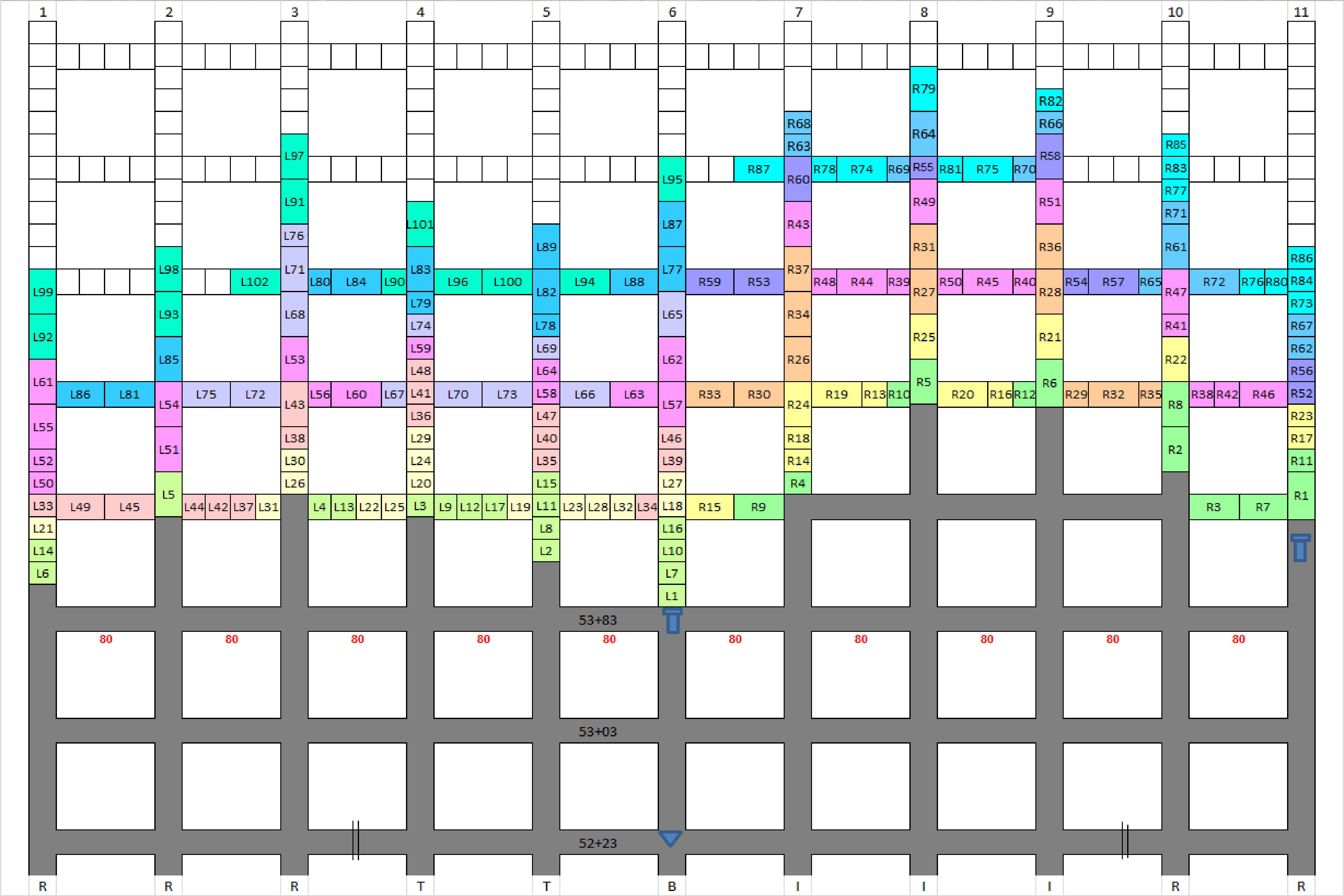
Actual Mining Sequence Day 1

Application Case Study

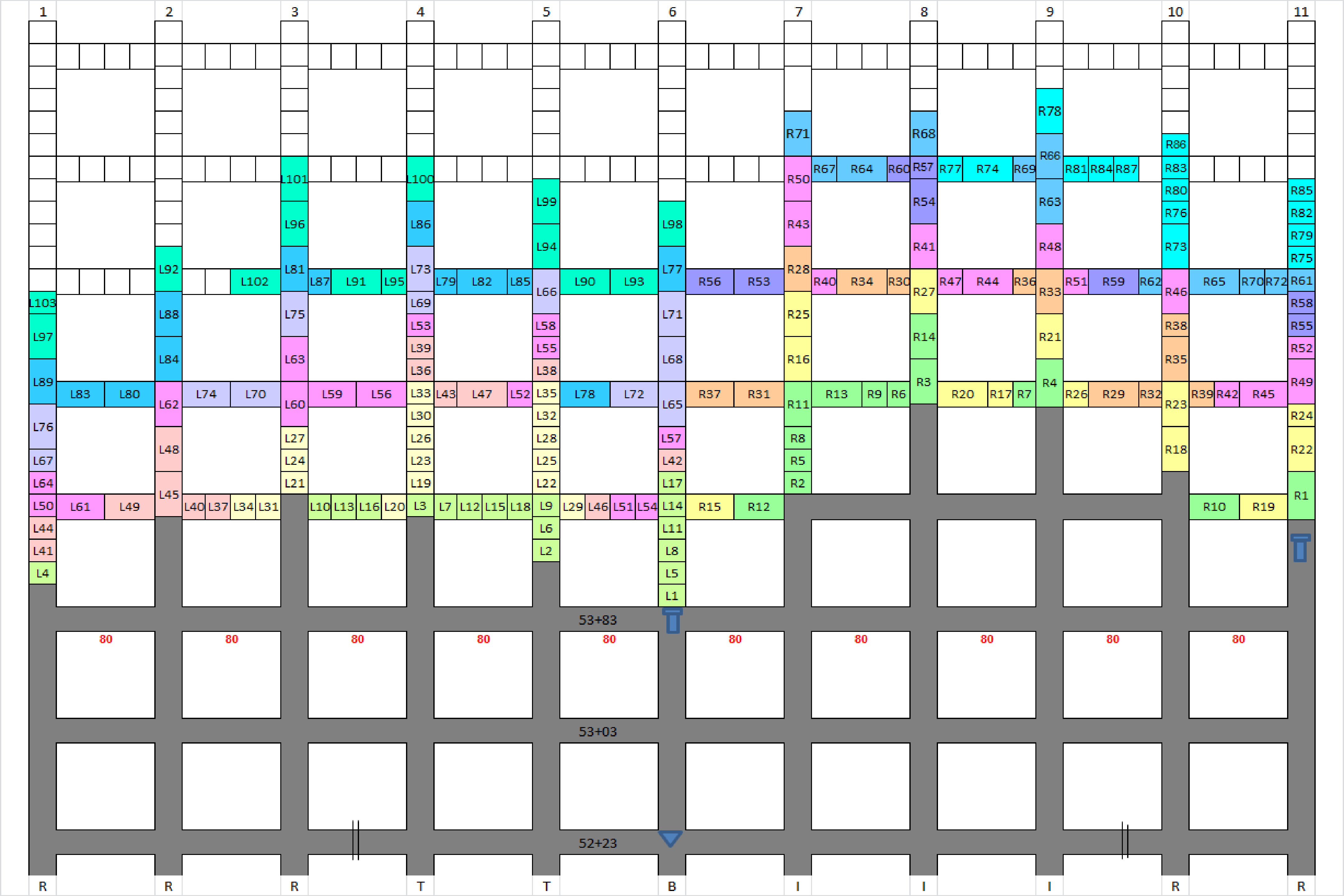


Predicted Optimal Mining Sequence for Day 12

Actual Mining Sequence for Day 12



1 2 3 4 5 6 7 8 9 10 11
R79
R82
R68 R66
R64
R63 R85
L97 R58
R87 R60 R78 R74 R69 R55 R81 R75 R70 R83
L95
L91 R77
L101 R49 R51
R71
L76 L89 L87 R43
R61
L98 L71 L83 L77 R37 R31 R36 R86
L102 L80 L84 L90 L96 L100 L94 L88 R59 R53 R48 R44 R39 R50 R45 R40 R54 R57 R65 R72 R76 R80 R84
L99 L82 R27 R28 R47
L79 R73
L93 L68 L65 R34
L74 L78 R41 R67
L92 R25 R21
L59 L69 R62
L85 L53 L62 R26 R22
L48 L64 R56
L61 R5 R6
L86 L81 L75 L72 L56 L60 L67 L41 L70 L73 L58 L66 L63 R33 R30 R19 R13 R10 R20 R16 R12 R29 R32 R35 R38 R42 R46 R52
L54 L43 L57 R24 R8
L36 L47 R23
L55
L38 L29 L40 L46 R18 R17
L51 R2
L52 L30 L24 L35 L39 R14 R11
L50 L26 L20 L15 L27 R4
L5 R1
L33 L49 L45 L44 L42 L37 L31 L4 L13 L22 L25 L3 L9 L12 L17 L19 L11 L23 L28 L32 L34 L18 R15 R9 R3 R7
L21 L8 L16
L14 L2 L10
L6 L7
L1
53+83
80 80 80 80 80 80 80 80 80 80
53+03
52+23
R R R T T B I I I R R



1 2 3 4 5 6 7 8 9 10 11
R78
R71 R68
R86
R66
L101 L100 R50 R67 R64 R60 R57 R77 R74 R69 R81 R84 R87 R83
L99 R80 R85
L96 L86 L98 R43 R54 R63 R76 R82
L94 R41 R48 R73 R79
L92 L81 L73 L77 R28 R75
L102 L87 L91 L95 L79 L82 L85 L66 L90 L93 R56 R53 R40 R34 R30 R27 R47 R44 R36 R33 R51 R59 R62 R46 R65 R70 R72 R61
L103 L69 R58
L88 L75 L53 L58 L71 R25 R14 R21 R38 R55
L97 L39 L55 R52
L84 L63 L36 L38 L68 R16 R35
L89 R3 R4 R49
L83 L80 L74 L70 L59 L56 L33 L43 L47 L52 L35 L78 L72 R37 R31 R13 R9 R6 R20 R17 R7 R26 R29 R32 R39 R42 R45
L62 L60 L65 R11 R23
L30 L32 R24
L76
L27 L26 L28 L57 R8
L67 L48 L24 L23 L25 L42 R5 R18 R22
L64 L21 L19 L22 L17 R2
L45 R1
L50 L61 L49 L40 L37 L34 L31 L10 L13 L16 L20 L3 L7 L12 L15 L18 L9 L29 L46 L51 L54 L14 R15 R12 R10 R19
L44 L6 L11
L41 L2 L8
L4 L5
L1
53+83
80 80 80 80 80 80 80 80 80 80
53+03
52+23
R R R T T B I I I R R

Application Case Study

Left-side CM

Day	AMS			OMS			Difference		
	Cuts	Feet Mined	CCT (min)	Cuts	Feet Mined	CCT (min)	Cuts	Feet Mined	CCT (min)
1	17	276	590	18	252	596	+1	-24	+6
2	15	221	508	17	229	503	+2	+8	-5
3	17	292	521	14	285	538	-3	-7	+17
4	15	375	662	15	384	624	0	+9	-38
5	12	343	600	12	375	598	0	+32	-2
6	13	384	612	13	357	610	0	-27	-2
7	13	394	651	14	402	675	+1	+8	+24
Totals	102	2285	4144	103	2284	4144	+1	-1	0

Right-side CM

Day	AMS			OMS			Difference		
	Cuts	Feet Mined	CCT (min)	Cuts	Feet Mined	CCT (min)	Cuts	Feet Mined	CCT (min)
1	12	314	544	14	348	556	+2	+34	+12
2	13	353	601	13	365	606	0	+12	+5
3	12	336	554	12	297	533	0	-39	-21
4	14	329	638	13	355	635	-1	+26	-3
5	9	245	419	8	214	415	-1	-31	-4
6	12	292	544	12	282	552	0	-10	+8
7	15	273	590	15	255	590	0	-18	0
Totals	87	2142	3890	87	2116	3887	0	-26	-3

Acknowledgements

- Southern Illinois University Carbondale & ICCI

- **Stan Suboleski** ***(SSP Model)***
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- **Prairie State Generating Corporation**
  Lively Grove Mine

2012 Illinois Mining Institute

QUESTIONS

on

Identifying Optimal Mining Sequences for Continuous Miner

Joseph C. Hirschi
Project Manager
Illinois Clean Coal Institute