2017 SME ANNUAL CONFERENCE & EXPO
CMA 119th NATIONAL WESTERN MINING CONFERENCE

Reliability-Based Capacity Determination Model for Semi-Mobile In-Pit Crushing & Conveying Systems

Bulk Material Handling: New Technology in BMH

Dr. Robert Ritter | 20.02.2017

Agenda

1 **Introduction**
Context | Problem & Objective

2 **Random Behaviour of System Elements**
Operational | Disturbance

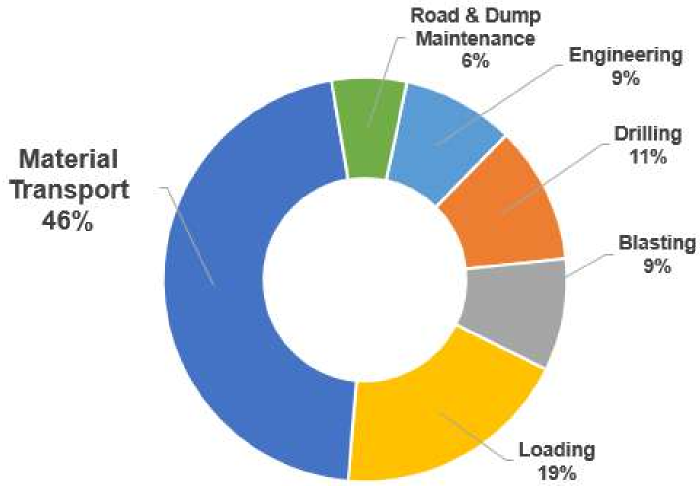
3 **System Capacity Model**
Hourly Loader Capacity | Effective Operating Time

4 **Case Study**
Mine | Results

5 **Summary**

Context

- Mine Planning Context
- Main Process: Material Transport
- Predominate → TRUCKS
- Overall Operational Cost Increase
- Material Transport Cost Increase



Context

More Material

Declining Ore Grades
Lead → 7% to 3.5% within 30 years

Increasing Stripping Ratios
Gold → 1:1 to 1:3 within 30 years

On Longer Distances

Increasing Mineralisation Depth

At Increased Cost

Increasing Labour Cost
Australia → increase of about 40% within 10 year

Governmental Cost Burdens
Canada (BC) → Carbon Tax – 30$/tonne

Belt Conveyors

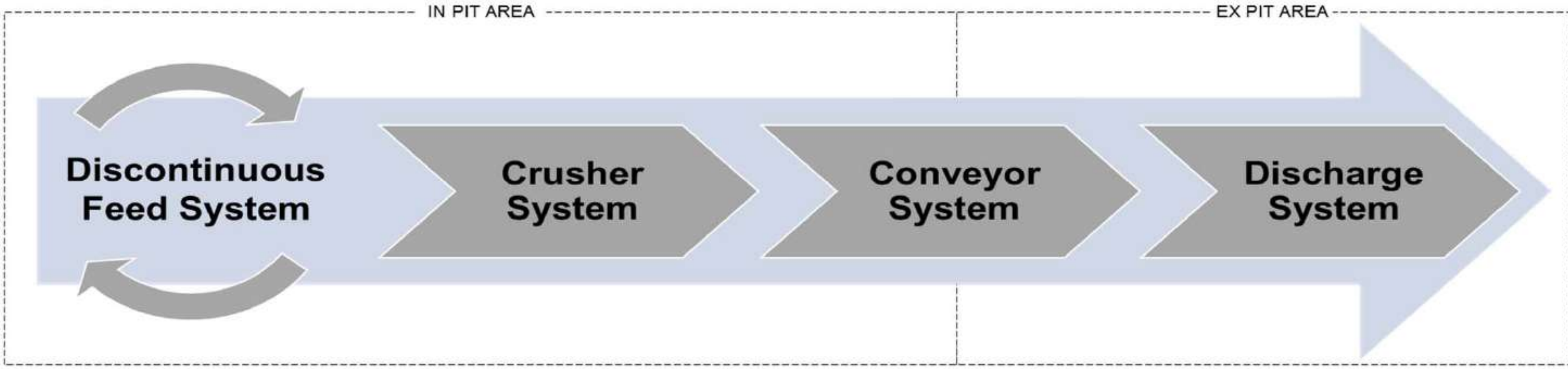
↓

Requires Crushing

↓

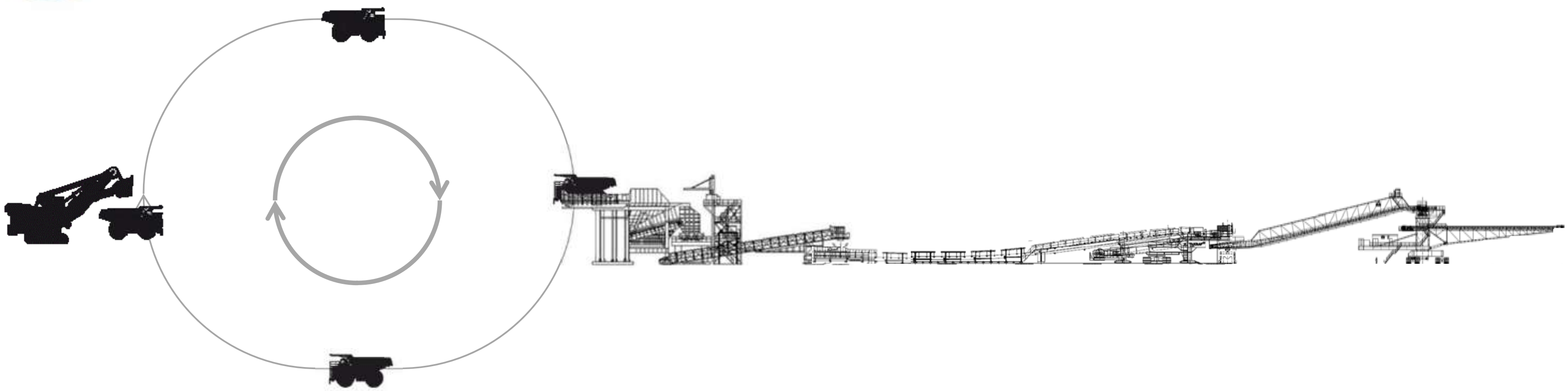
In-Pit Crushing and Conveying Systems

In-Pit Crushing and Conveying System



Discontinuous Part	Continuous Part

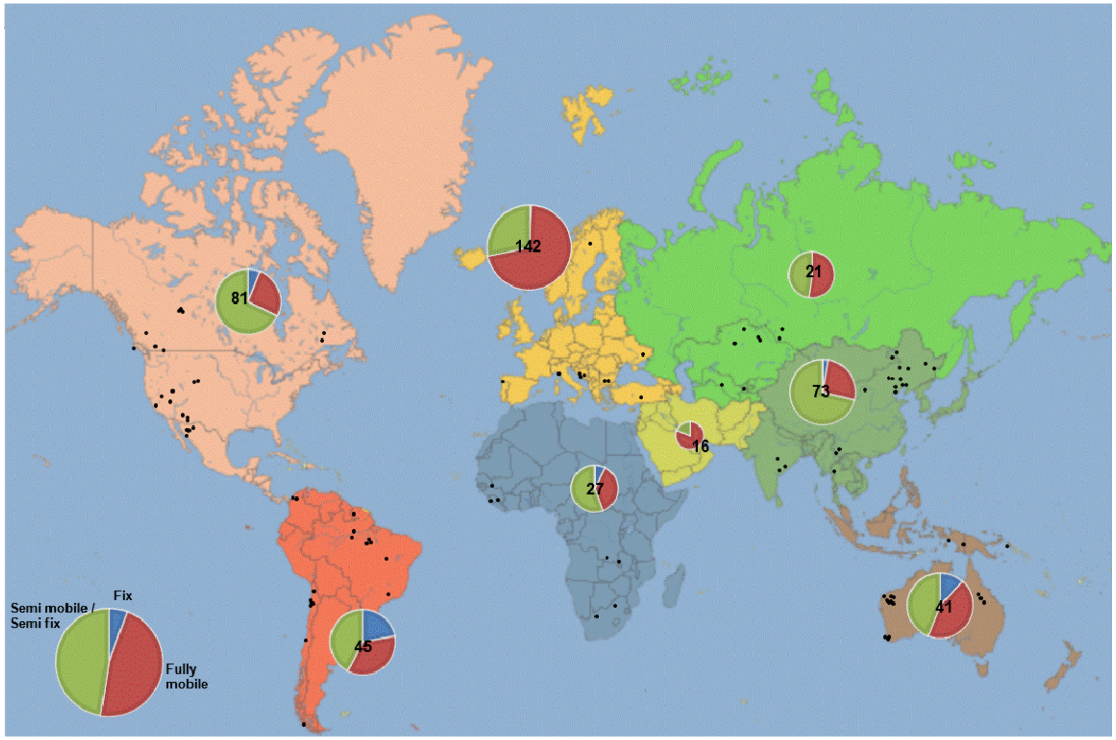
Semi-Mobile In-Pit Crushing and Conveying System (SMIPCC)



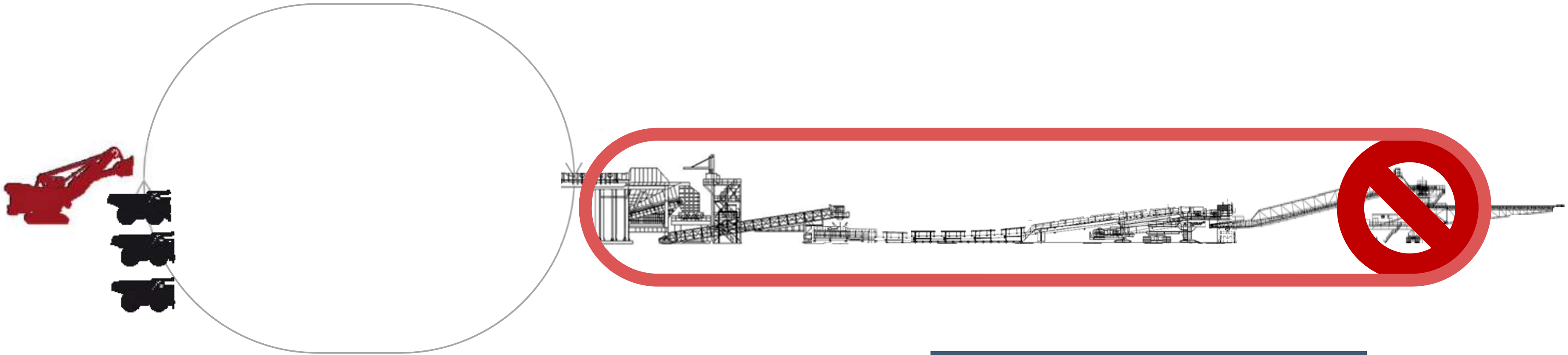
Loading	Intermitted Truck Haulage	Crushing	Conveying	Discharge
Discontinuous Part		Continuous Part		

Problem Statement

- IPCC Systems not a Novelty
- Some failed to live up to
  - Capacity &
  - Cost Expectations
- Unsuitable Methods neglect
  - Variance
  - Disturbances



Objective



Loa

Objective

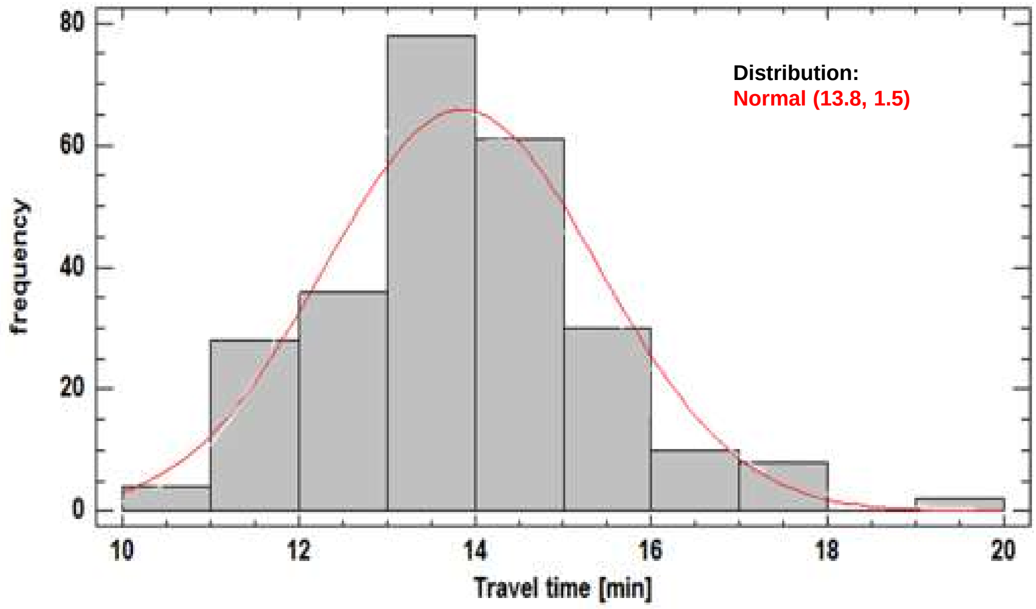
Crushing

scharge

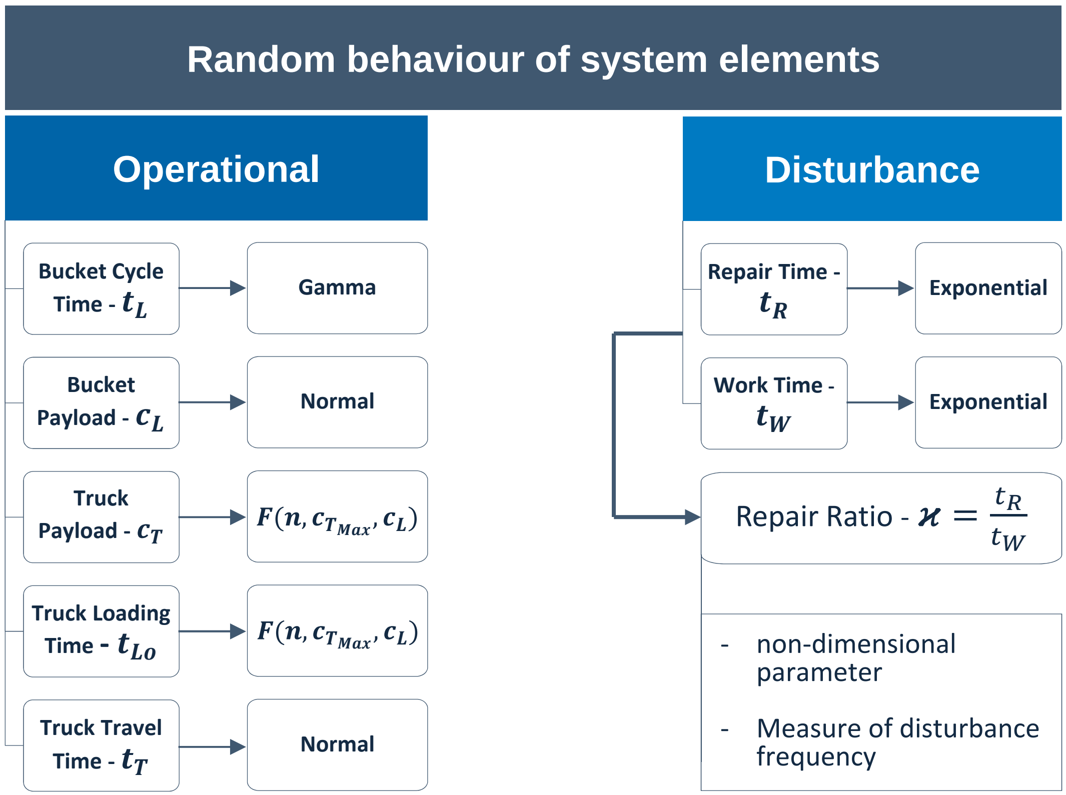
Develop a structured method to estimate SMIPCC systems capacity under consideration of the random behaviour of system elements

Random Behaviour of System Elements

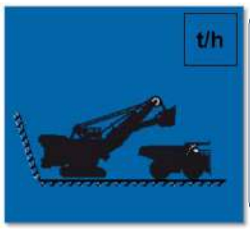
- Fluctuation of operational process time
- Random variables
- Described by PDF
- Statistic Analysis based on
  - Time studies
  - Data sets



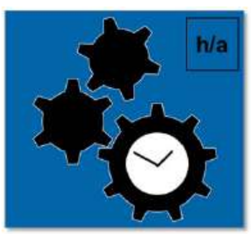
Random Behaviour of System Elements - Results



SMIPCC System Capacity Model



Hourly Loader Capacity C_L



Effective Operating Time - Loader t_{Oe}

Annual System Capacity C_S

$$C_S = C_L \cdot t_{Oe}$$

Hourly Loader Capacity C_L

Mean Truck Payload $\bar{c}_T$

Truck Loading Time $\bar{t}_{Lo}$

Hourly Loader Capacity C_L

$$C_L = \bar{c}_T \cdot \frac{3600}{\bar{t}_{Lo}}$$

$$f_{c_T}(x) = \left[\sum_{n=1}^{\infty} \varphi(x; n\mu_{c_L}, \sigma_{c_L}^2)\right]\left(1 - \Phi\left(\frac{c_{T_{max}} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right)$$

$$f_{t_{Lo}}(x) = \sum_{i=1}^{\infty} g(x; n\sigma_{t_{Lo}}^2/\mu_{t_{Lo}}, \mu_{t_{Lo}}^2/\sigma_{t_{Lo}}^2) \cdot \left[\Phi\left(\frac{c_{T_{max}} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}}\right) - \Phi\left(\frac{c_{T_{max}} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}}\right)\right]$$

Hourly Loader Capacity - C_L

Deterministic Approach

$$\bar{N} = \frac{\bar{c}_{T_{max}}}{\bar{c}_L} = \frac{165t}{50t} \approx 3$$

$$\bar{c}_T = \bar{N} \cdot \bar{c}_L = 3 \cdot 50t = 150t$$

$$\bar{t}_{Lo} = \bar{N} \cdot \bar{t}_L = 3 \cdot 25s = 75s$$

- Example:
  - Bucket Payload $\bar{c}_T = 50t$
  - Bucket Cycle Time $\bar{t}_L = 25s$
  - Maximum Payload of Truck $c_{Tmax} = 165t$

Hourly Loader Capacity - C_L

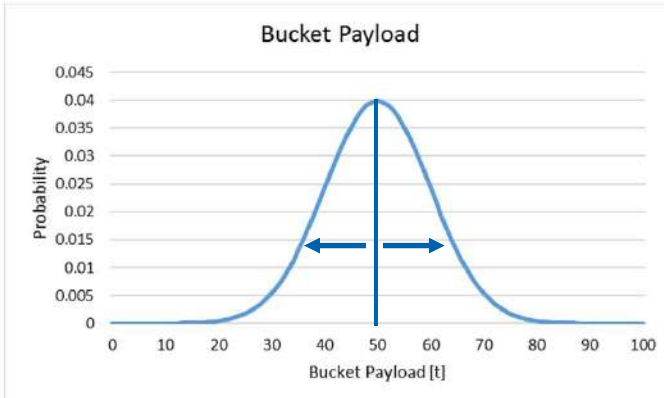
Stochastic Approach

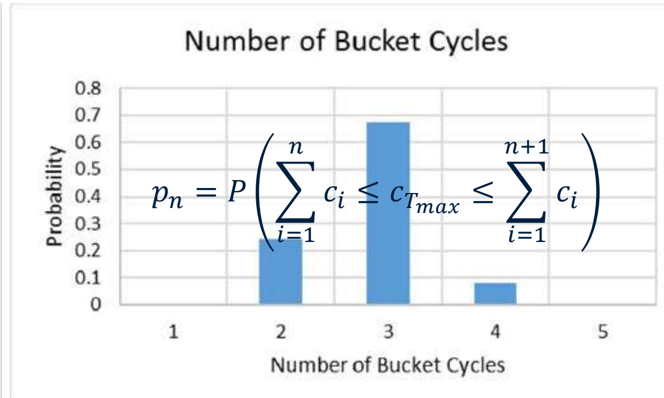
$$\bar{c}_L \sim N(50, 10^2)$$

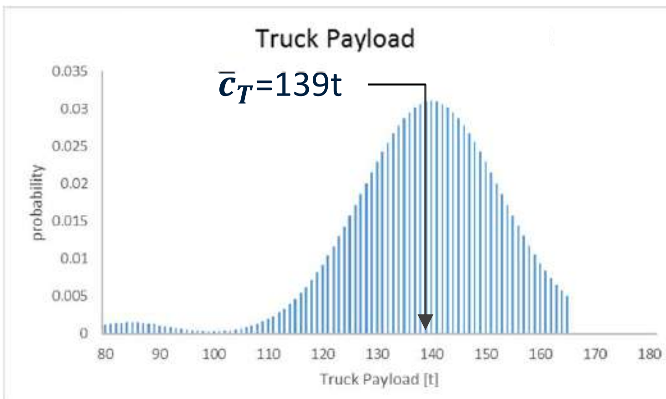
$$\bar{N} = 2.85$$

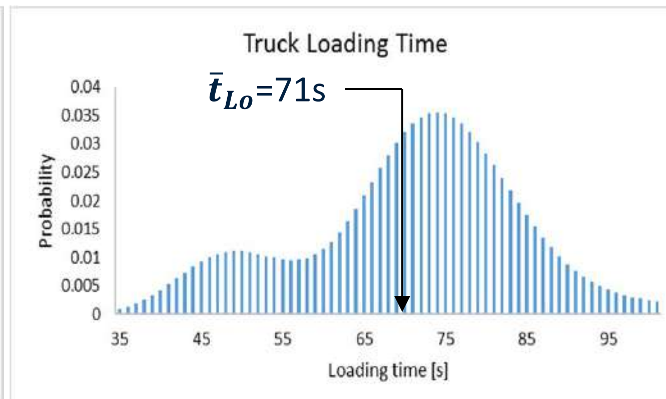
$$\bar{c}_T = 139.4t$$

$$\bar{t}_{Lo} = 71.3s$$









Hourly Loader Capacity - C_L

Deterministic Approach

$$C_L = 150t \cdot \frac{3600}{75s}$$

$$\boldsymbol{C_L = 7,200t/h}$$

Stochastic Approach

$$C_L = 139.4t \cdot \frac{3600}{71.3s}$$

$$\boldsymbol{C_L = 7,038t/h}$$

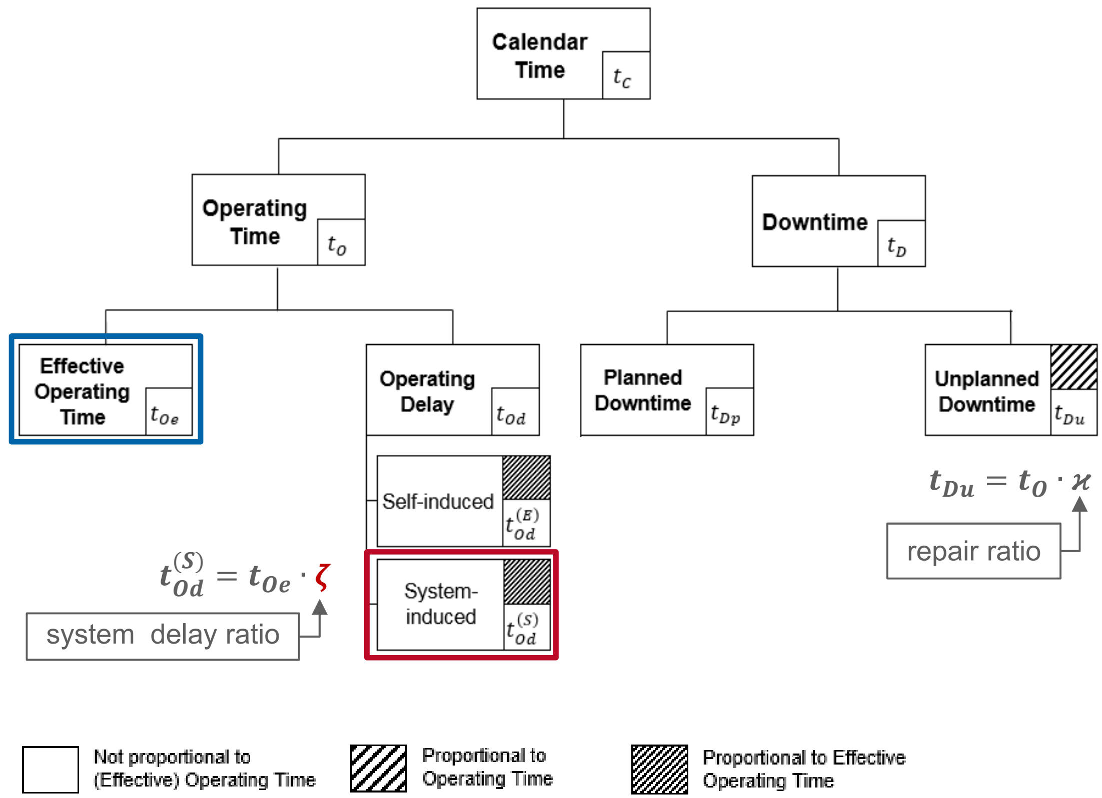
$$\Delta_{c_L} \approx \boldsymbol{162t/h}$$

Effective Operating Time t_{Oe}

Time Usage Model

- Structures time quantities
- Establishes logical relations

$$t_{O_e} = \frac{t_C - t_{Dp}^{(1)} - t_{Dp}^{(2)} - t_{Dp}^{(3)} - t_{Dp}^{(4)} - t_{Dp}^{(5)''}}{(1 + \nu + \zeta + \tau) + (1 + \nu + \zeta)\varkappa}$$



Simulation Model for ζ

- Stochastic simulation model
- Written in VBA

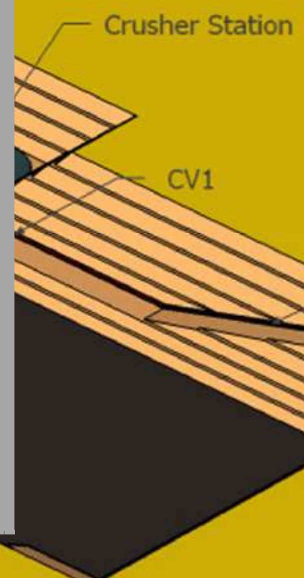
Case Study

- Based on a Clermont coal mine
- SMIPCC system setup:

P&H4100 – Komatsu 930 – Crusher Station

– 6 Conveyor flights – Spreader

- Appropriate input values
- $C_L = 9,398 t/h$



Case Study - Analyses

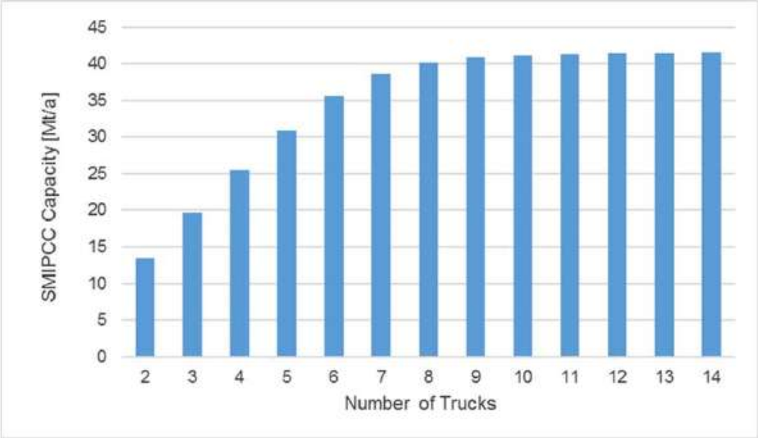
Analysis 1
Various truck quantities

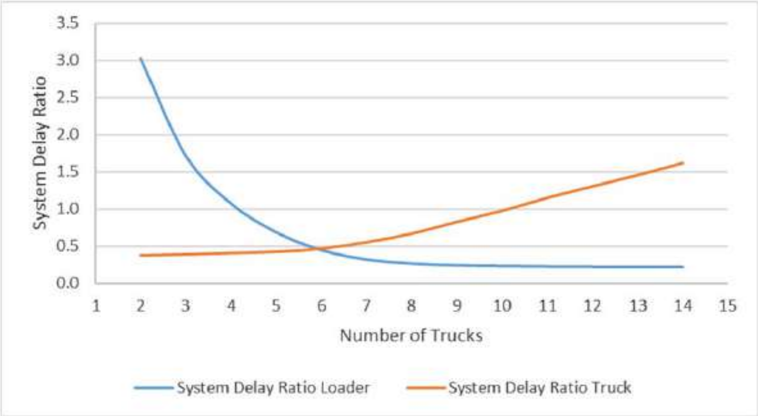
Analysis 2
Economic analysis

Analysis 3
Sensitivity analysis

Analysis 4
Stockpile

Analysis 5
Comparison





Results

- $C_S \uparrow$ as $n_T \uparrow$
- Diminishing marginal returns
- Limit at 41.5 Mt
- $\zeta_L \downarrow$ as $n_T \uparrow$
- $\zeta_T \uparrow$ as $n_T \uparrow$

Case Study - Analyses

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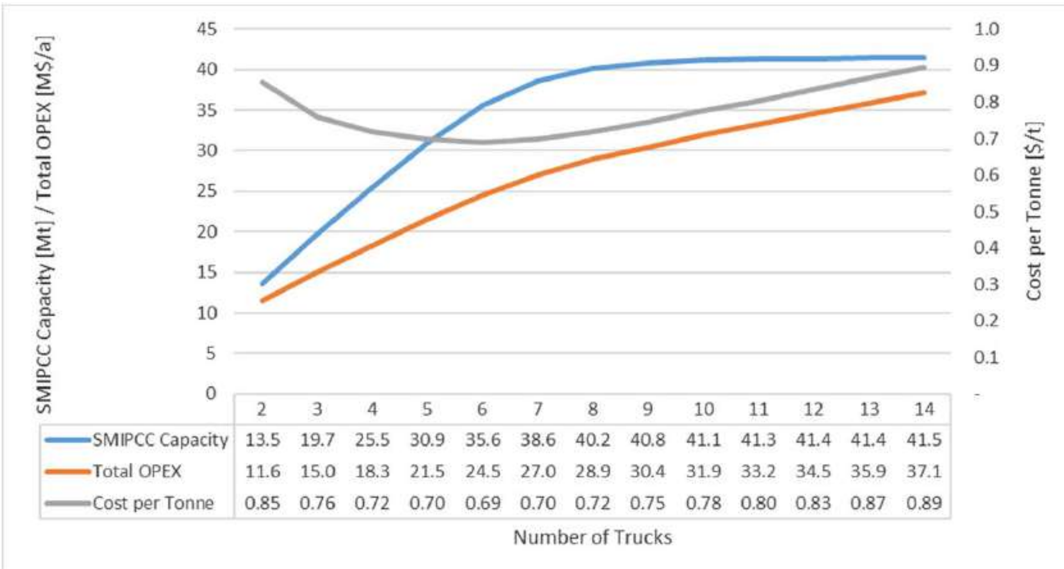

Number of Trucks	2	3	4	5	6	7	8	9	10	11	12	13	14
SMIPCC Capacity	13.5	19.7	25.5	30.9	35.6	38.6	40.2	40.8	41.1	41.3	41.4	41.4	41.5
Total OPEX	11.6	15.0	18.3	21.5	24.5	27.0	28.9	30.4	31.9	33.2	34.5	35.9	37.1
Cost per Tonne	0.85	0.76	0.72	0.70	0.69	0.70	0.72	0.75	0.78	0.80	0.83	0.87	0.89

Results

- Cost per tonne approach a minimum
- @ 6 Trucks
- With 0.69 $/t
- At about 37Mt/a

Case Study - Analyses

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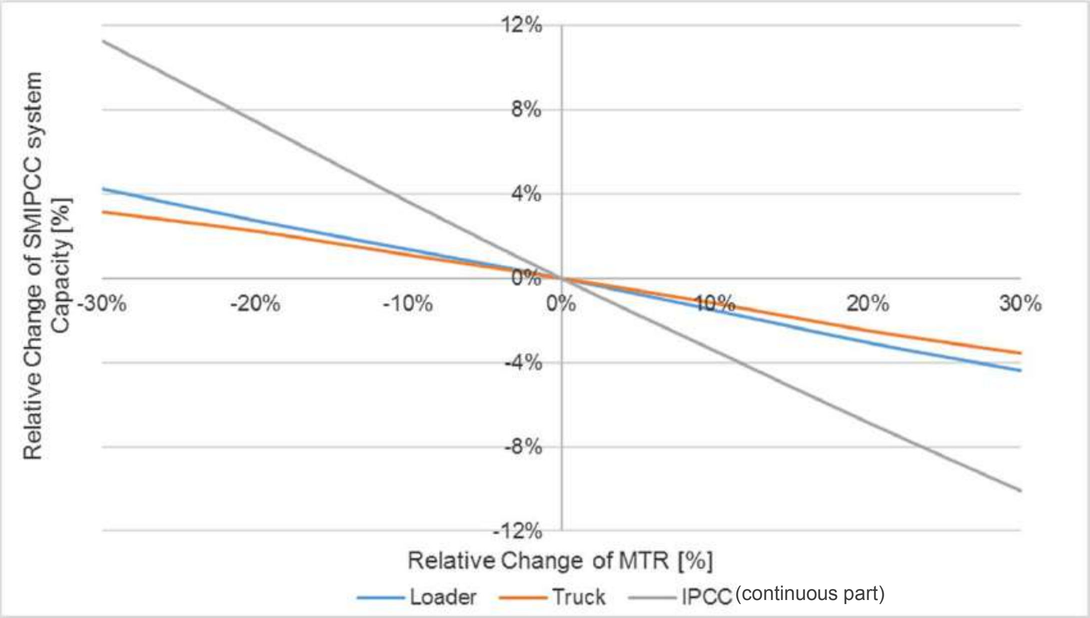

Results

- Linear relation between C_S and MRT
- C_S ↑ as MRT↓
- -30% MRT_{IPCC} → +11% C_S

Case Study - Analyses

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Various truck quantities

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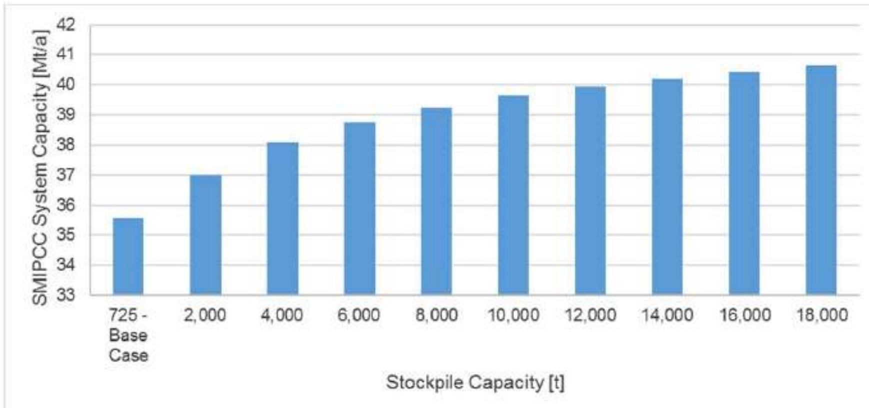

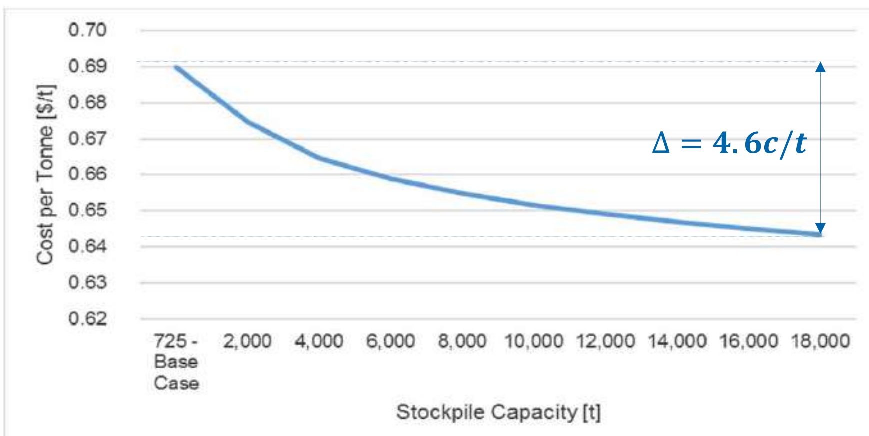

Results

- $C_S \uparrow$ as $C_{Stock} \uparrow$
- $C_S \uparrow$ by 5Mt @18,000t
- Diminishing marginal returns
- Cost reduction to base case -4.6c/t

Case Study - Analyses

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Various truck quantities

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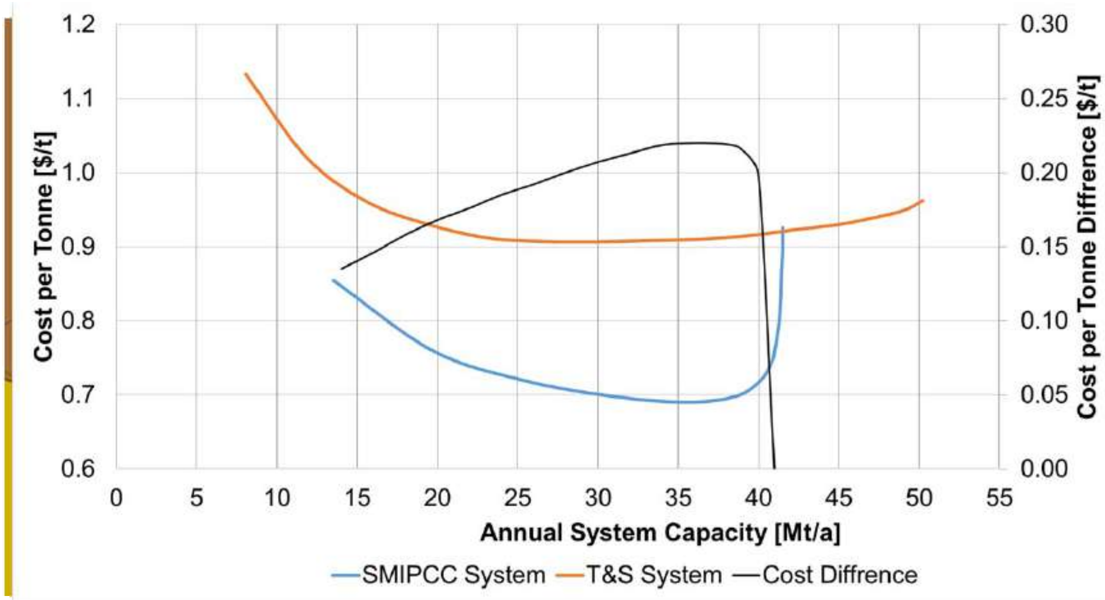


Assumption

- Truck travel time increased by 2.5

Results

- $OPEX_{IPCC} < OPEX_{T\&S}$
  $\Delta = 0.14\ - 0.22\$/t$

Summary

1. Quantification of disturbance parameters
2. Development of a stochastic hourly loader capacity method
3. Structured Time Usage Model specific to IPCC
4. Stochastic simulation model for system delay ratio
5. Descriptive conclusions to lay out new SMIPCC systems

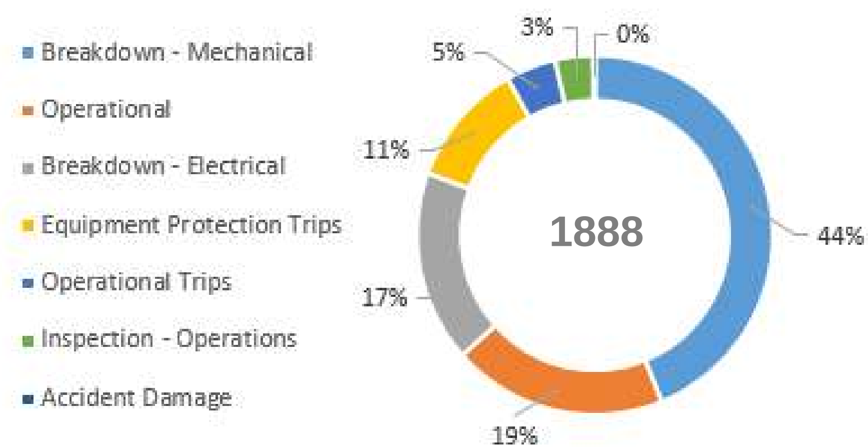
TAKRAF
TENOVA

Clermont Coal Mine

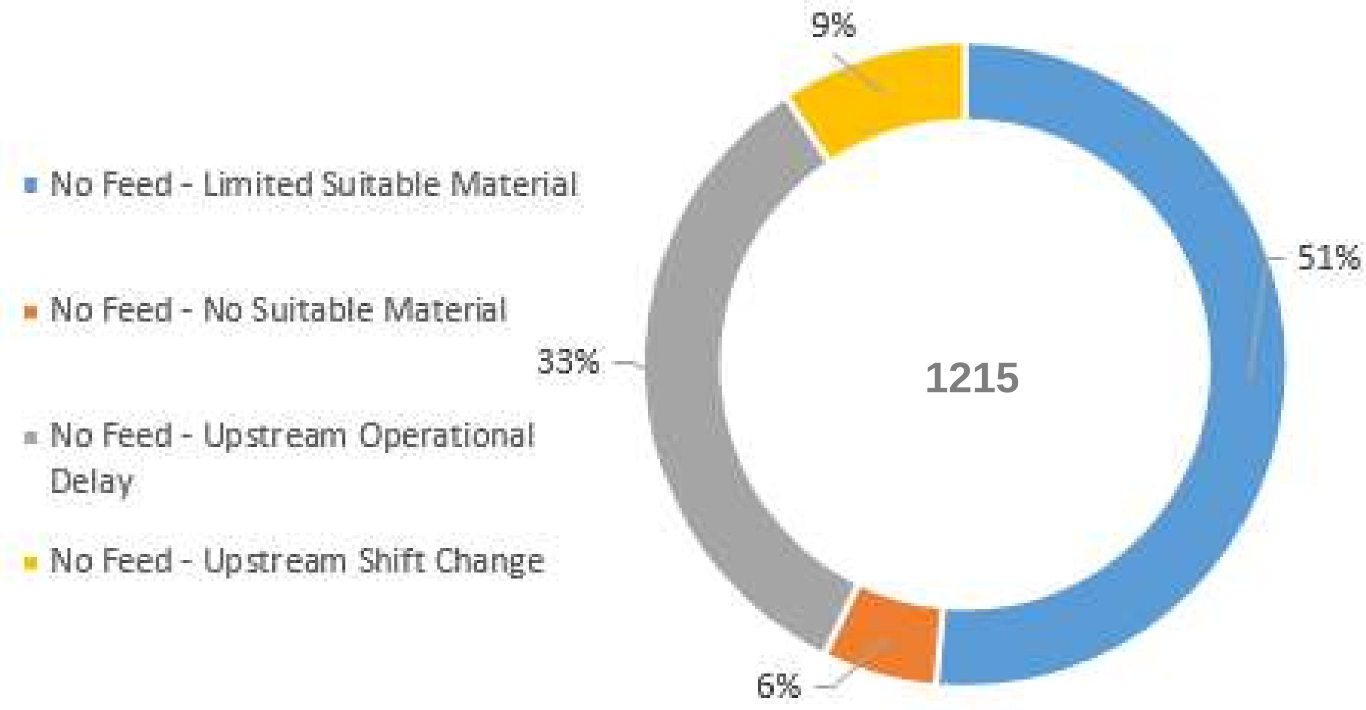
Transitions:

Start of operation: 2010

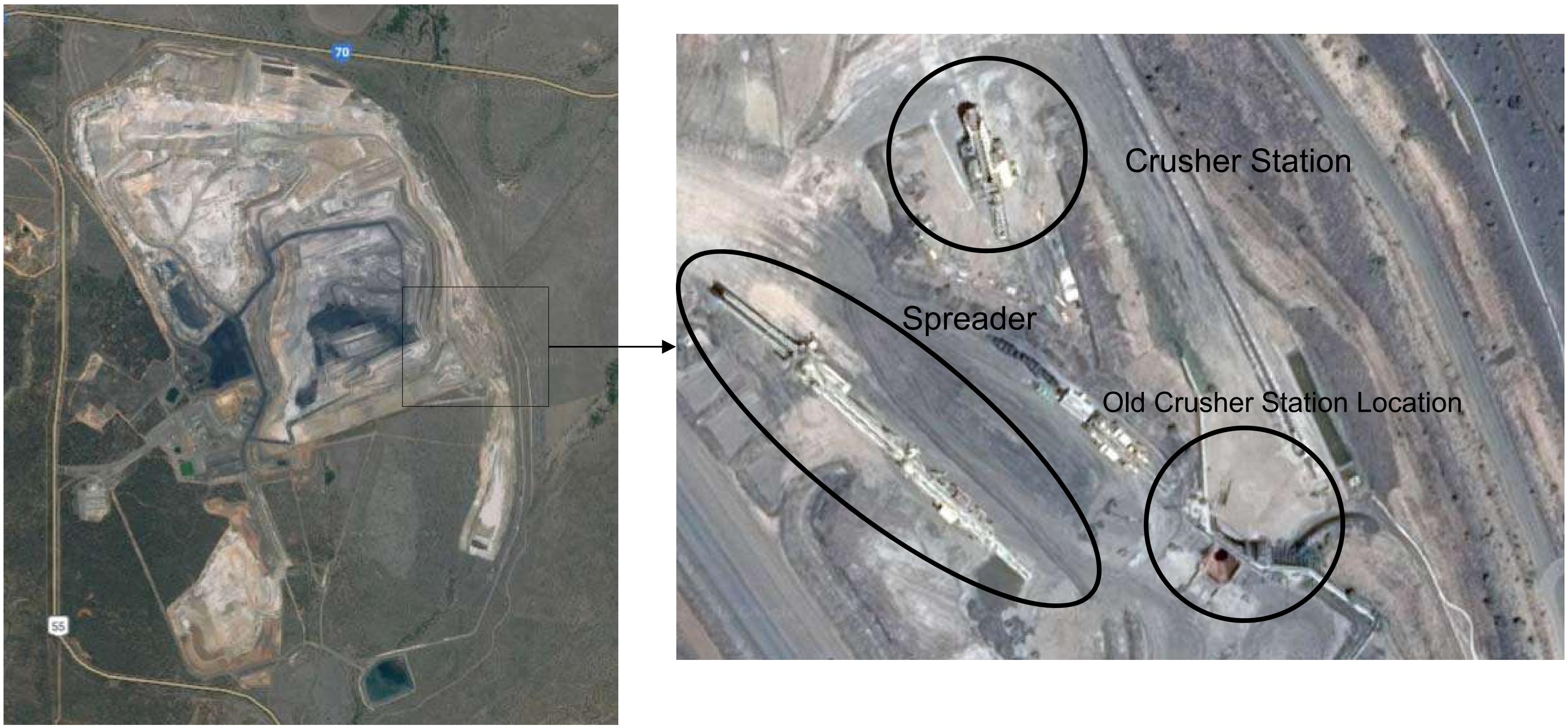
1. FMIPCC to SMIPCC (inpit) – right after start
2. SMIPCC (inpit) to SMIPCC (expit) – Mar.2012
3. Stop of operation – Oct. 2015



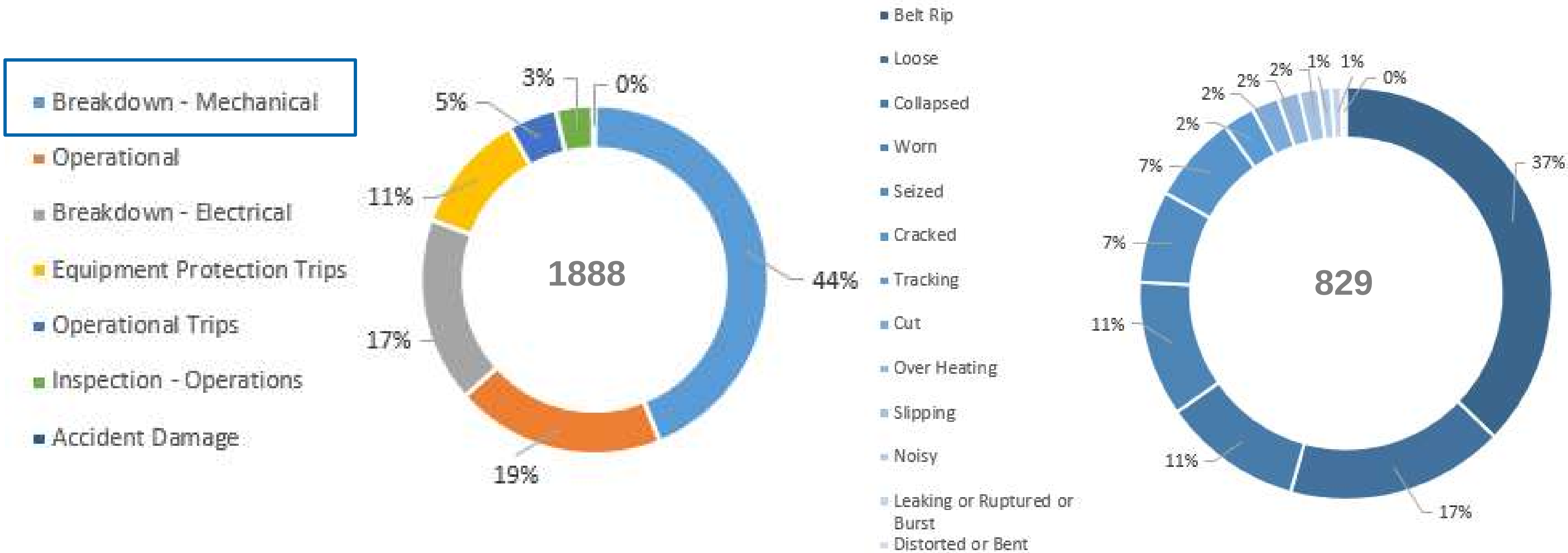
Clermont
Operating Delay – System Induced Operating Delay



Clermont Coal Mine



Clermont Unplanned Downtime Breakdown



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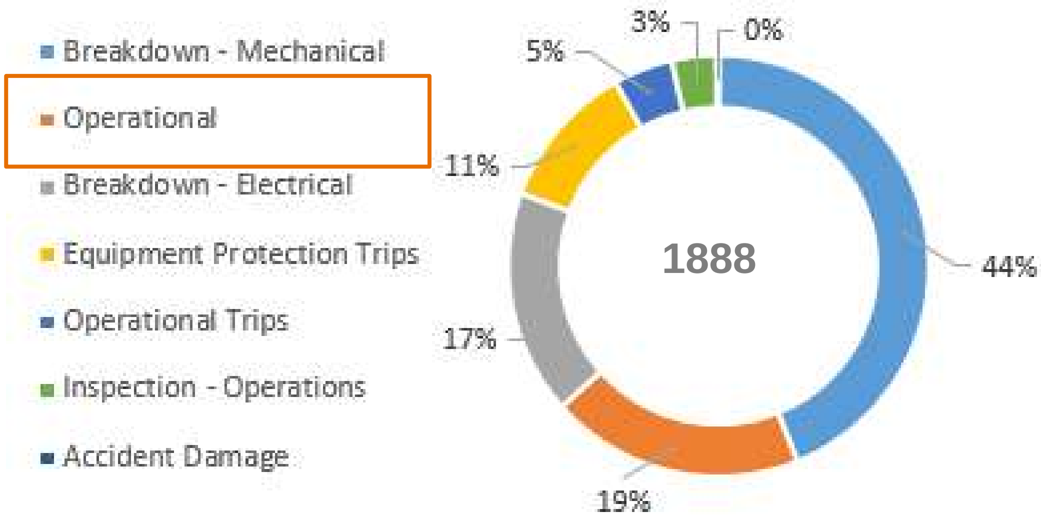

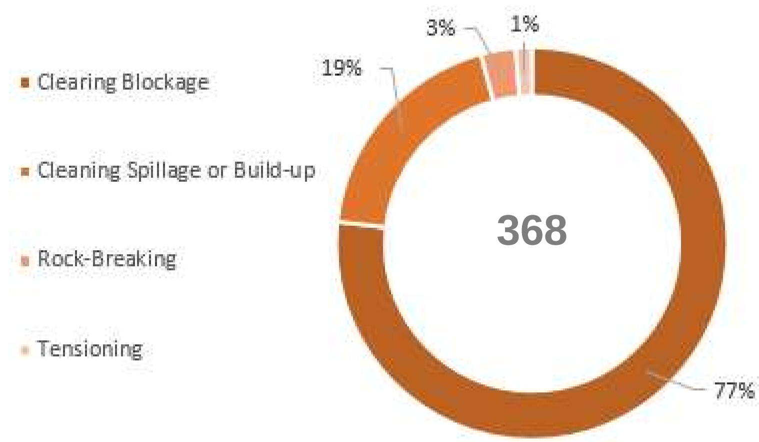

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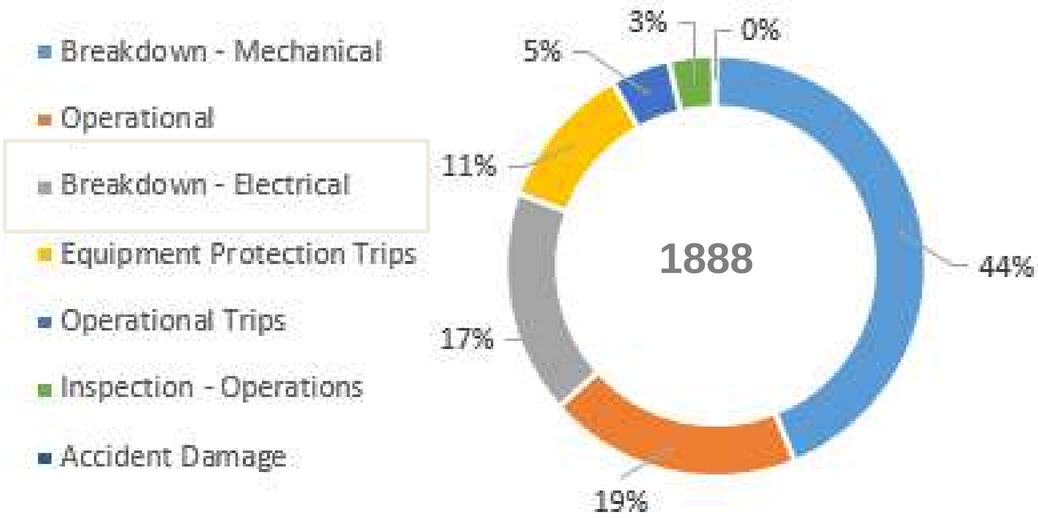
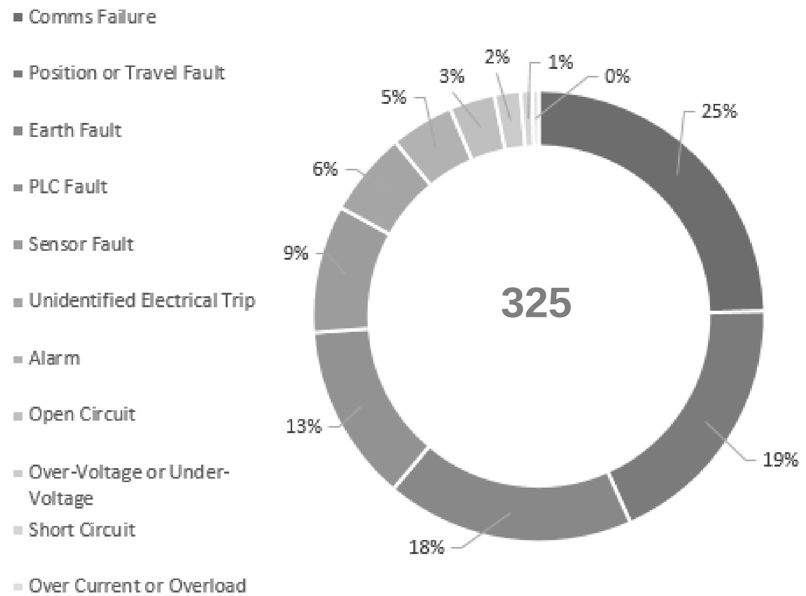
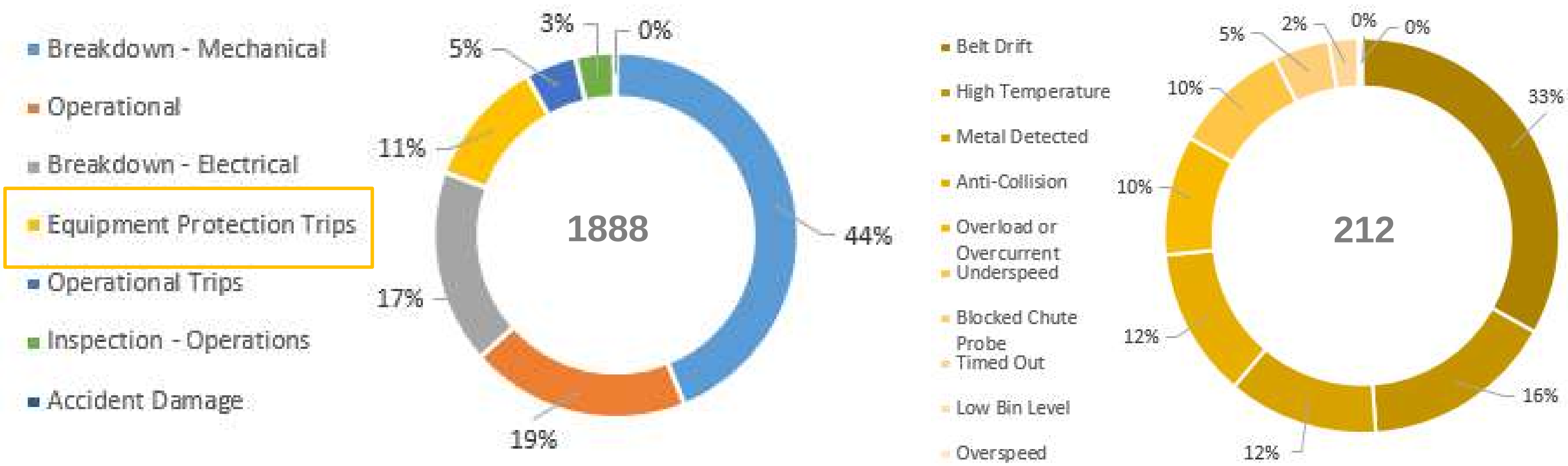
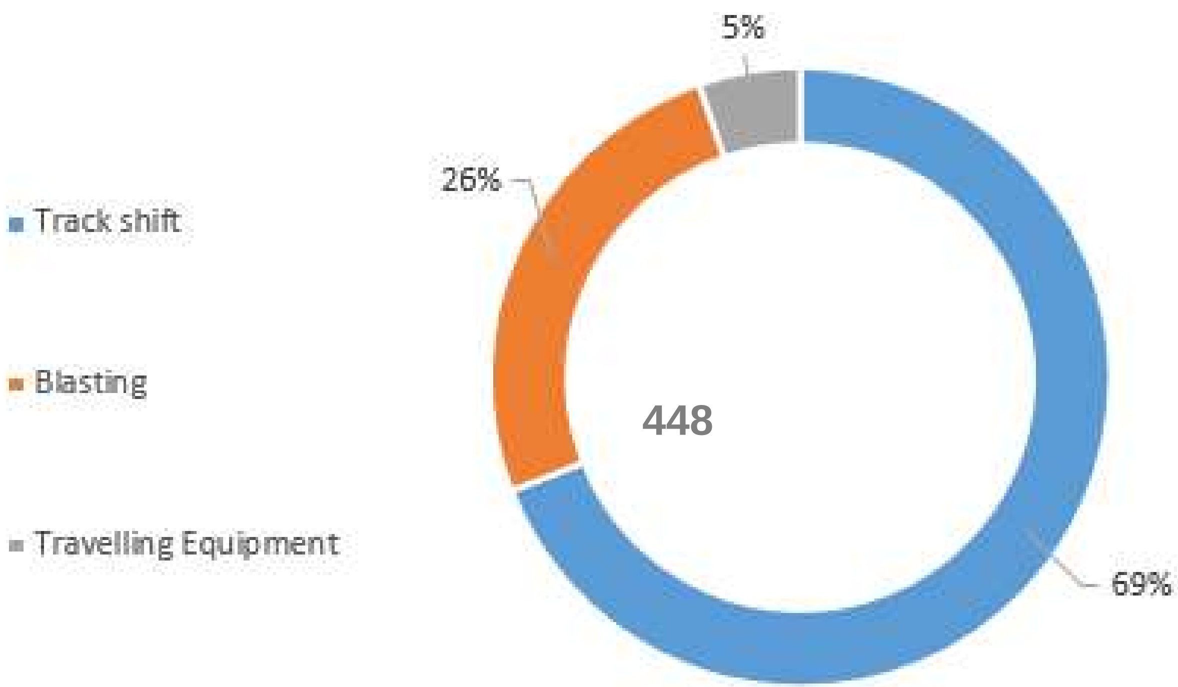




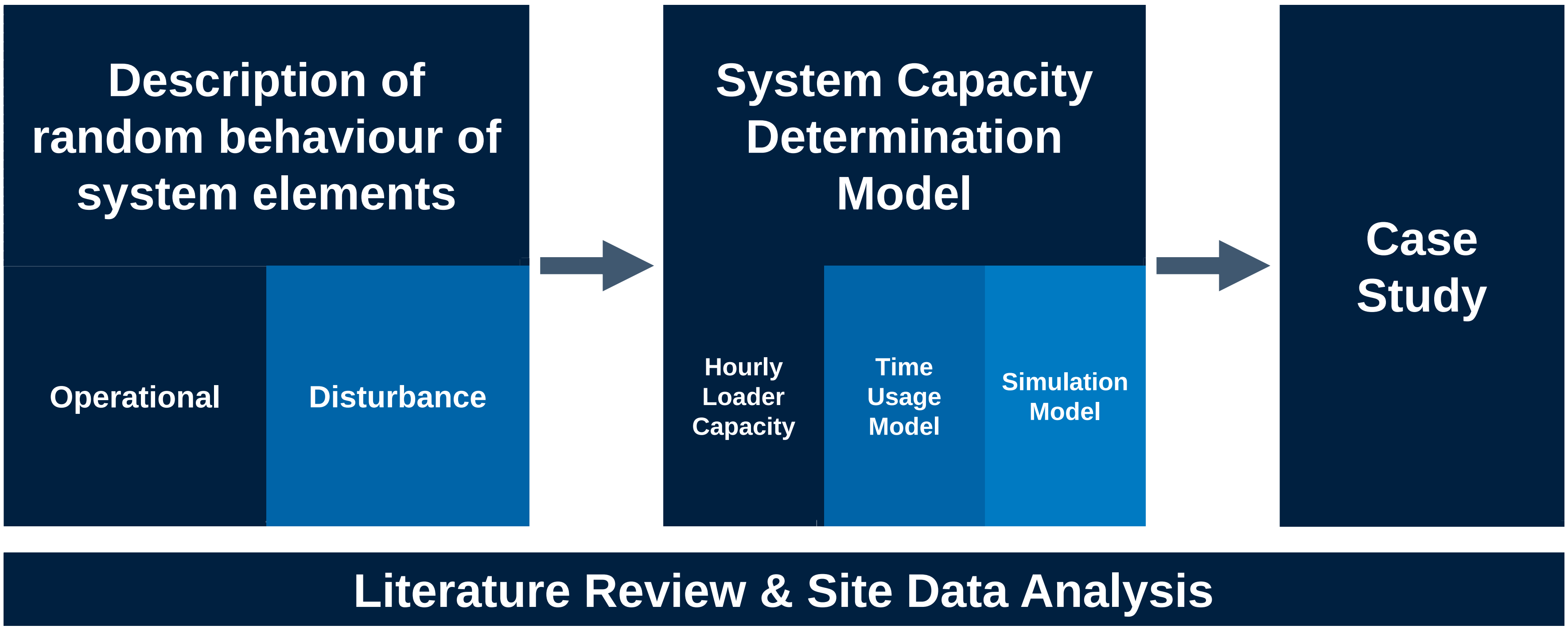
Clermont Unplanned Downtime Breakdown



Clermont
Technological Downtime



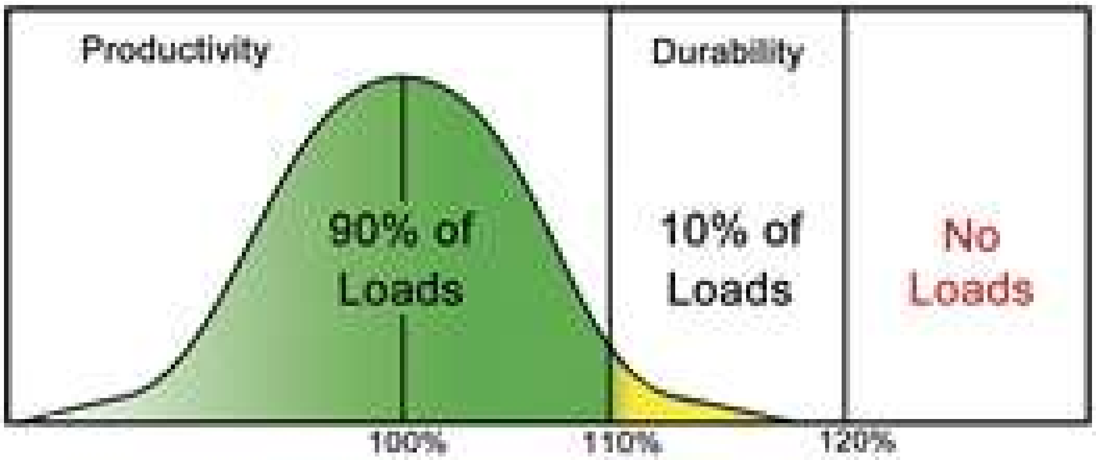
Methodology



Critical Discussion of Results

1. Work Time Distribution
2. Alteration of Truck Allocation
3. Preventative Maintenance for Trucks
4. Trucks in Reserve
5. Increasing Truck Travel Times

10/10/20 Truck Loading Policy



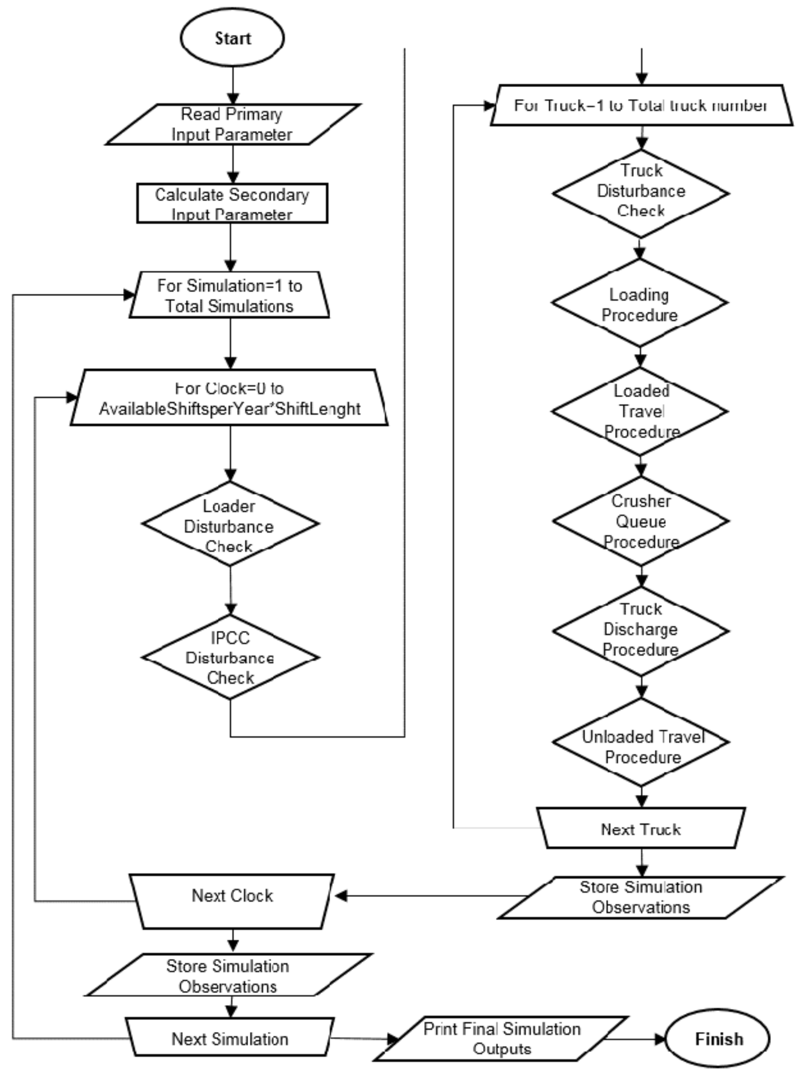
"No more than 10% of payloads may exceed 1.1 times the target payload and no single payload shall ever exceed 1.2 times the target payload "

Random Disturbance Behaviour of System Elements

Equipment type	Mean Repair Time [min]	Mean Work Time [min]	Repair Ratio
Loader			
cable shovel	132.7	790	0.17
hydraulic excavator	288.1	1,991	0.157
Trucks	296.7	963	0.128
Crusher	33.1	458	0.117
Spreader	52.1	1,147	0.059
Conveyor			
shiftable	32.7	2,162	0.019
relocatable	31.8	5,834	0.012
fix	21	20,780	0.007

Simulation Model

- Goal → system delay ratio ζ
- VBA in Excel
- Simulation Model Description
  - Initialization
  - Disturbance Check
  - Truck Loop
  - Loader Queue Procedure
  - Loading Procedure
  - Travel Procedure
  - Crusher Queue Procedure
  - Truck Discharge Procedure



Number of Bucket Cycles - Formular

$$p_n = P(N = n) = P\left({c_T}^{(n)} \leq c_{T_{max}} \leq {c_T}^{(n+1)}\right)$$

$$= P\left({c_T}^{(n)} \leq c_{T_{max}}\right) - P\left({c_T}^{(n+1)} \leq c_{T_{max}}\right)$$

$$= P\left(\frac{{c_T}^{(n)} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}} \leq \frac{c_{T_{max}} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}}\right) - P\left(\frac{{c_T}^{(n+1)} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}} \leq \frac{c_{T_{max}} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}}\right)$$

$$= \Phi\left(\frac{c_{T_{max}} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}}\right) - \Phi\left(\frac{c_{T_{max}} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}}\right)$$

Truck Payload – Equations I

Based on the above it is now possible to describe the distribution function $F_{c_T}(x)$ of the truck payload. It is clear that $c_L \leq x \leq c_{T_{max}}$. $F_{c_T}(x)$ can be expressed as

Where $F_{C_T|N=n}(x)$ is the distribution function $F_{c_T}(x)$ under the condition that n passes are handled and under the consideration of the truck payload policy.

Using

$$F_{c_T|N=n}(x) = P\left(c_T^{(n)} \leq x \middle| N = n\right) = \frac{P(c_T^{(n)} \leq x, N = n)}{p_n}$$

$$= \frac{P(c_T^{(n)} \leq x, c_T^{(n)} \leq c_{T\,max} < c_T^{(n+1)})}{p_n}$$

$$= \frac{P(c_T^{(n)} \leq x, c_{T\,max} < c_T^{(n+1)})}{p_n}$$

Truck Payload – Equations II

It can be seen that

$$F_{c_T}(x) = \sum_{n=1}^{\infty} P(c_T^{(n)} \leq x, c_{T_{max}} < c_T^{(n+1)})$$

$$= \sum_{n=1}^{\infty} \int_{-\infty}^{x} \int_{c_{T_{max}}-x}^{\infty} \varphi(x; n\mu_{c_L}, n\sigma_{c_L}^2)\varphi(y; n\mu_{c_L}, \sigma_{c_L}^2) dxdy$$

$$= \sum_{n=1}^{\infty} \int_{-\infty}^{x} \varphi(x; n\mu_{c_L}, n\sigma_{c_L}^2) \left(1 - \Phi\left(\frac{c_{T_{max}} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right) dx.$$

Truck Payload – Equations III

Practically, the sum of c_i only extends over a few n (usually between 2 and 7 bucket cycles). In particular, for a sufficiently large $c_{T_{max}}$. Therefore, the probability density function of c_T can be derived as the following holds

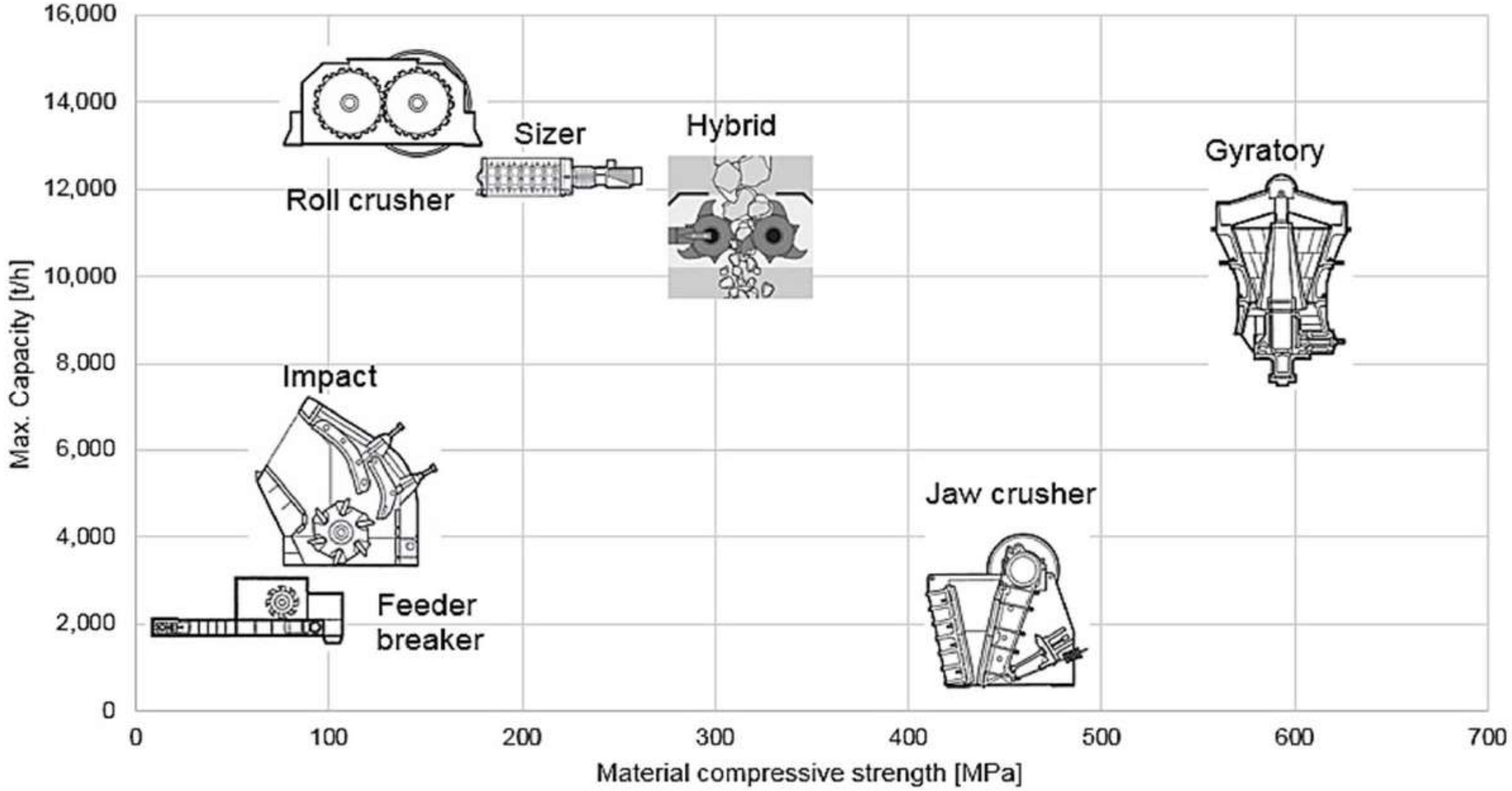
$$f_{c_T}(x) = \left[\sum_{n=1}^{\infty} \varphi\left(x; n\mu_{c_L}, \sigma_{c_L}^2\right)\right]\left(1 - \Phi\left(\frac{c_{T\,max} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right).$$

Thus the mean and variance of c_T can be written as

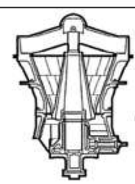
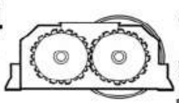
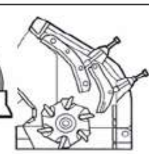
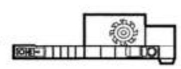
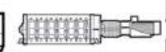
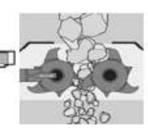
$$\bar{c}_T = \int_0^{c_{T\,max}} x \sum_{n=1}^{\infty} \varphi(x; n\mu_{c_L}, \sigma_{c_L}^2 \left(1 - \Phi\left(\frac{c_{T\,max} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right) dx$$

$$\sigma_{C_T}^2 = \int_0^{c_{T\,max}} (x - \bar{c}_T)^2 \sum_{n=1}^{\infty} \varphi(x; n\mu_{c_L}, \sigma_{c_L}^2 \left(1 - \Phi\left(\frac{c_{T\,max} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right) dx\,.$$

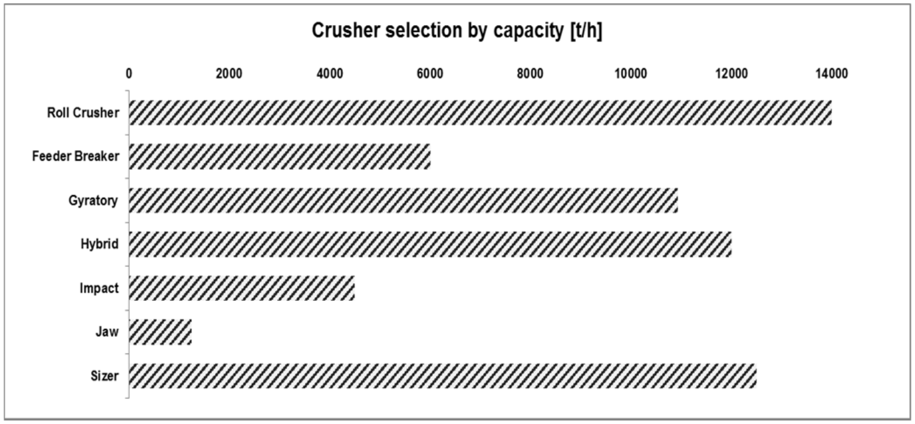
Crusher Type Overview

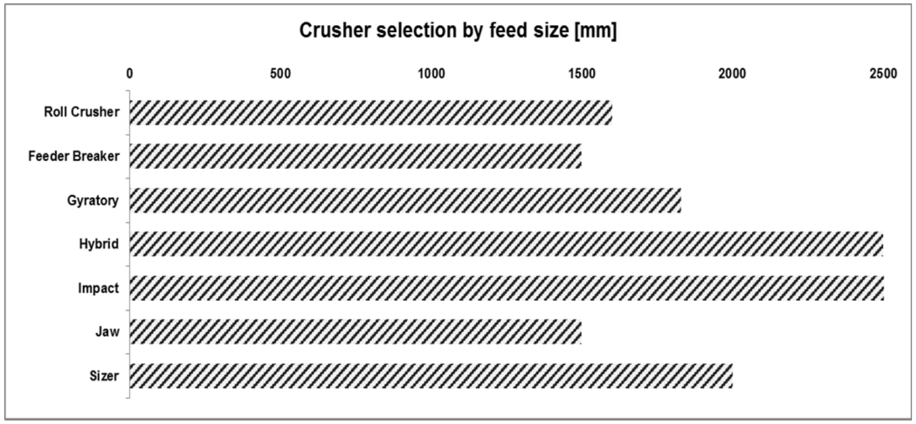


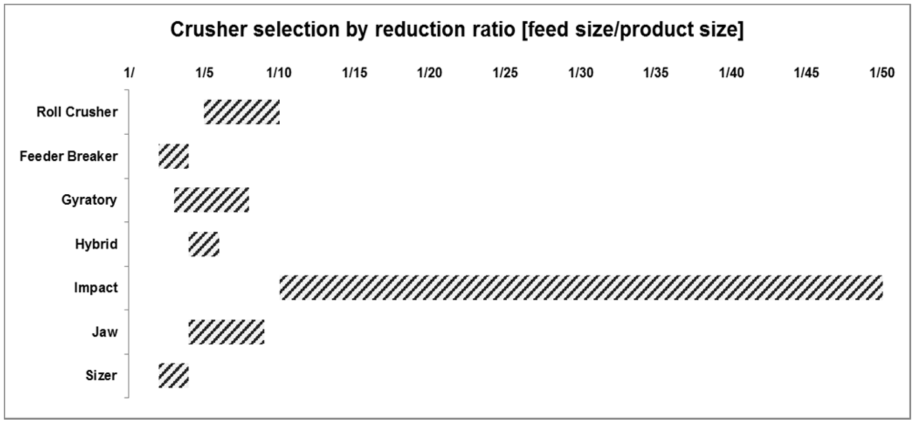
Crusher Type Overview

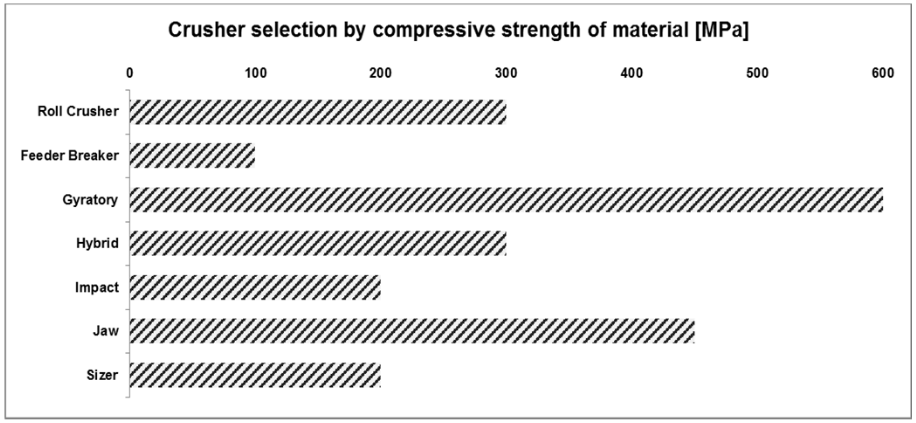
Crusher		Jaw	Gyratory	Roll Crusher	Impact	Feeder Breaker	Sizer	Hybrid
Year introduced		1858	1883	1910	1920	1960	1979	2005
Mechanical reduction method		compression	compression	compression, impact & shear (for single roll)	impact, attrition, shear	compression, impact, shear	shear, compression	compression
Moisture content [%]		<5	<5	>20	<10	>20	<20	>20
Application for high clay materials		poor - fair	poor	good	poor	fair	excellent	very good
Abrasiveness		high	high	low	not applicable	low	low - medium	low - medium
Fine generation		low-medium	low-medium	low	high	low-medium	low	low
Max. capacity [t/h]		1250	10940	14000	4500	6000	12500	12000
Material compressive strength [MPa]		450	600	150	115	50	200	300
Max. feed size [mm]		1500	1830	1600	3000	1500	2000	2500
Reduction ratio		1:4 - 1:9	1:3 - 1:8	1:5 - 1:10	1:10 - 1:50	1:2 - 1:4	1:2 - 1:4	1:4 - 1:6
Design variations		single/double toggle	Gyratory, Jaw-type gyratory	Single/double roll	Horizontal/vertical and single/double shaft		single/double roll, side/centre	
Max. Dimensions [mm]	height	5400	10800	3500	8100	2000	1800	2000
	length	5200	6450	9700	5500	6500	10100	9300
	width	4200	6250	8200	5700	4500	4050	7000
Max. Weight [t]		115	530	230	190	50	190	102
Max. Installed power [kW]		400	1200	2000	2800	300	1200	2500
Schematic								

Crusher Type Properties

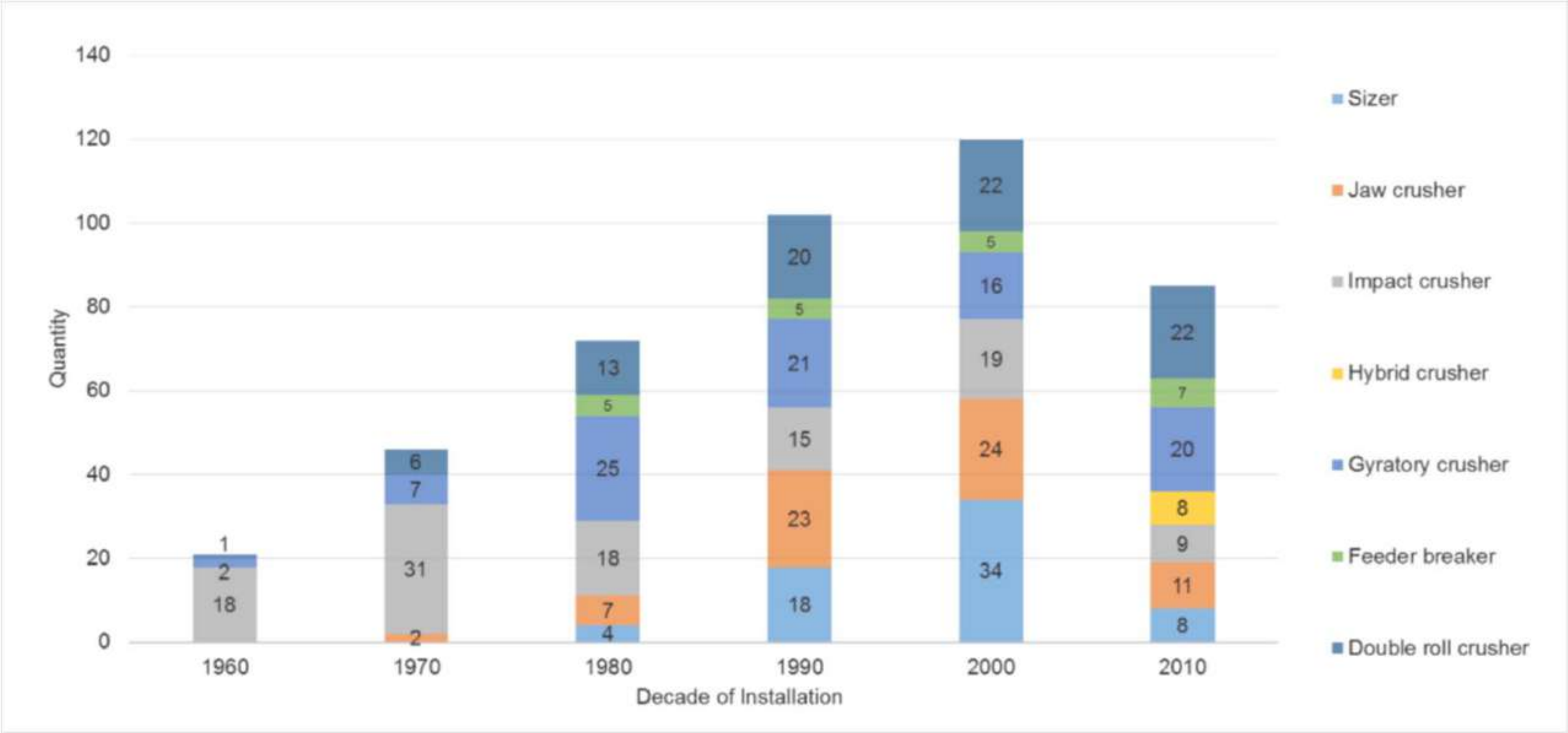




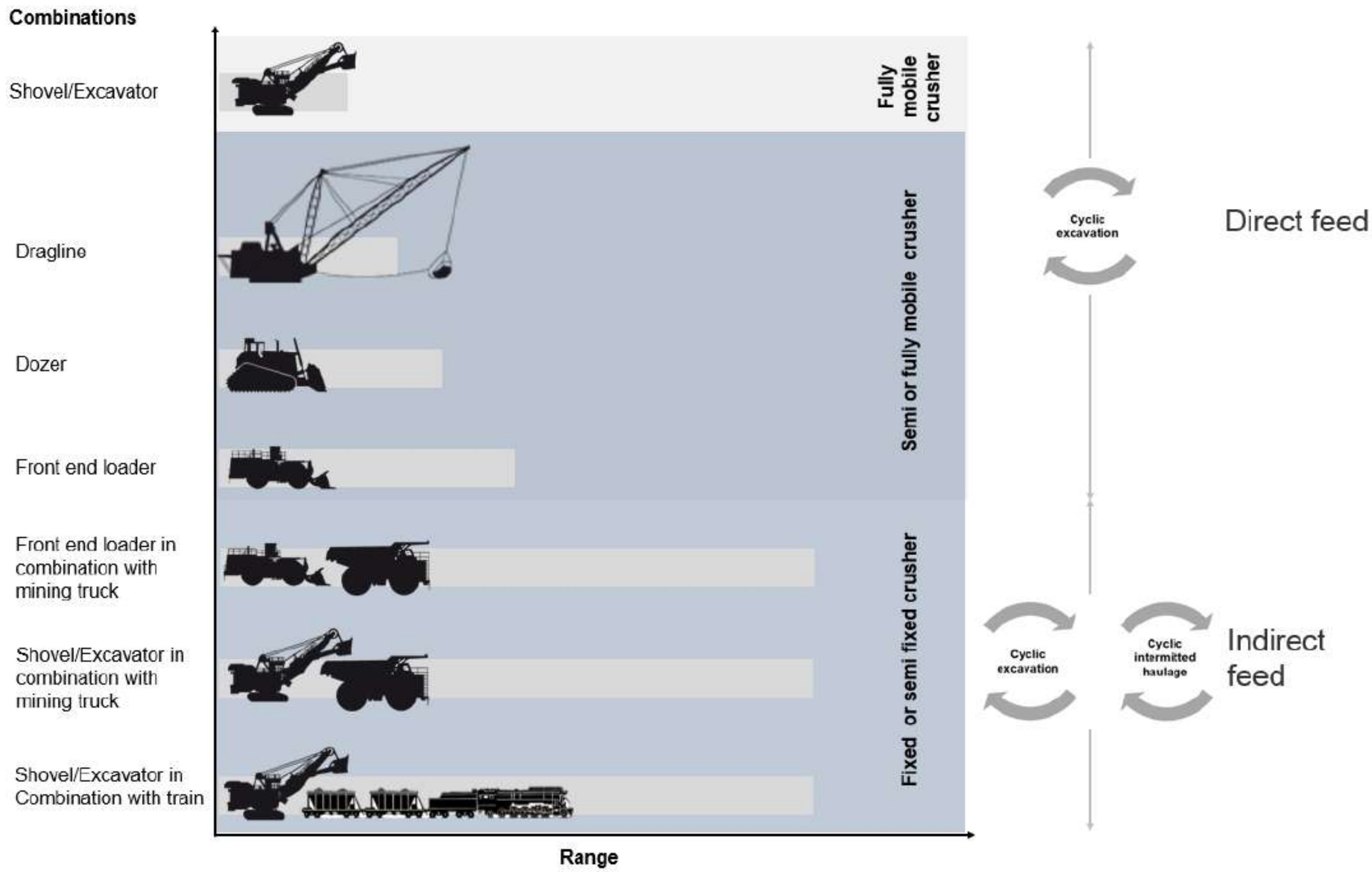




Change of Crusher Types over Decades



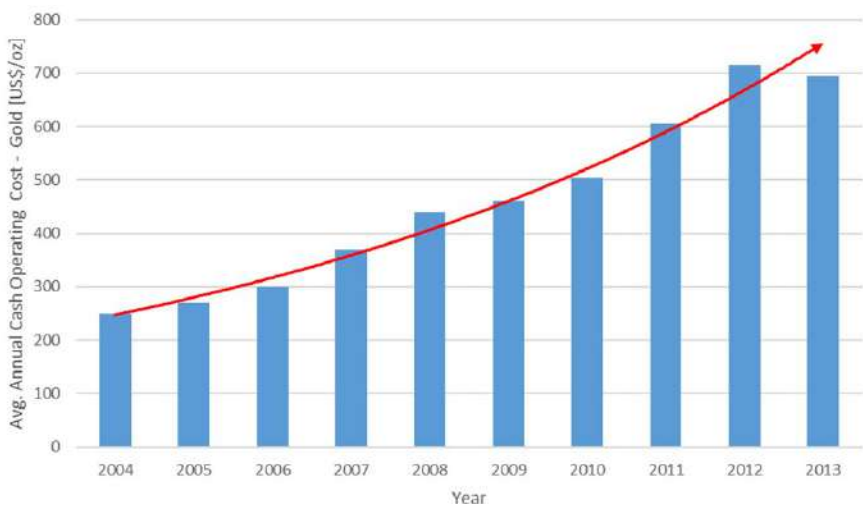
Feed System


Combinations
Shovel/Excavator
Dragline
Dozer
Front end loader
Front end loader in combination with mining truck
Shovel/Excavator in combination with mining truck
Shovel/Excavator in Combination with train
Fully mobile crusher
Semi or fully mobile crusher
Fixed or semi fixed crusher
Range
Cyclic excavation
Direct feed
Cyclic excavation
Cyclic intermitted haulage
Indirect feed

Background – Challenges

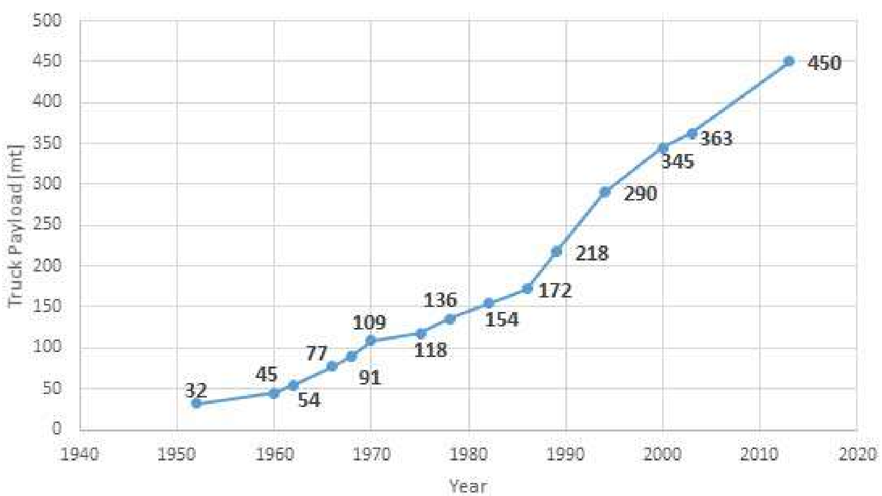
- Material transport as the main process in mining
- Today's predominate mean of material transport - TRUCKS
- However…

OPEX Development



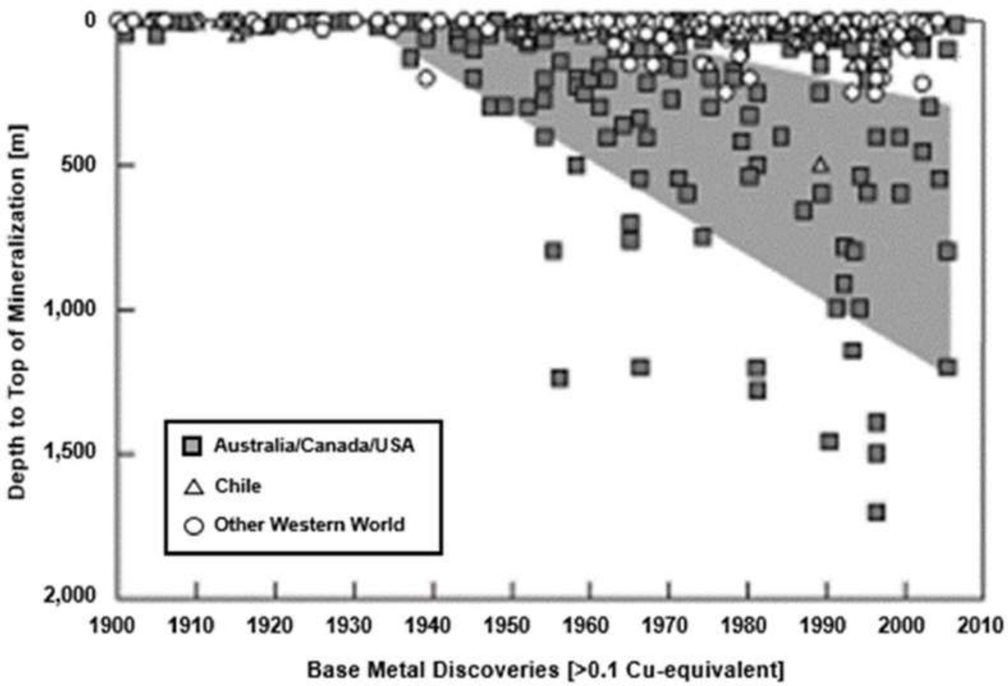
Source: SNL Metals and Mining´s Strategies for Gold Reserve Replacement

Mining Truck Evolution



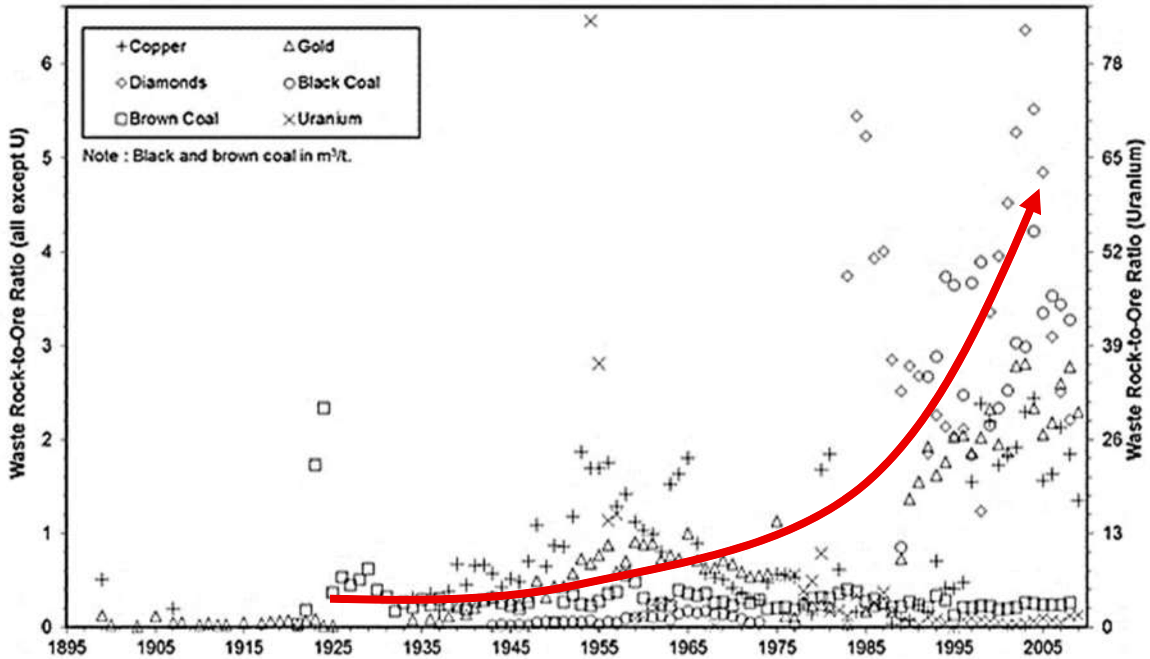
After Bozorgebrahimi, 2004

Increase of Mineralisation Depth



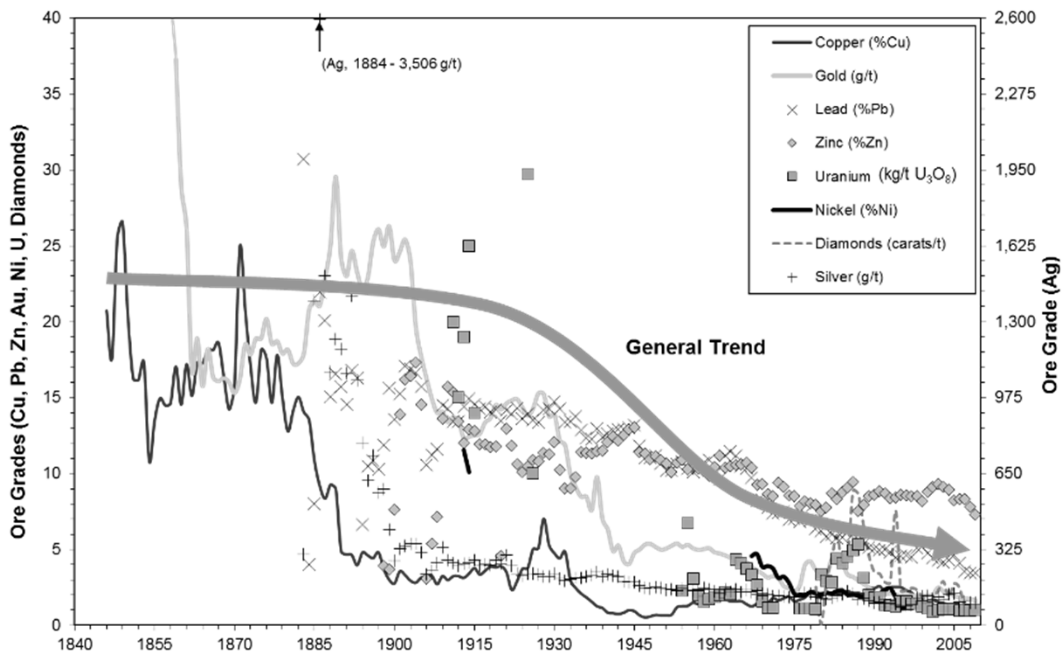
Randolph, 2011

Increasing Stripping Ratios



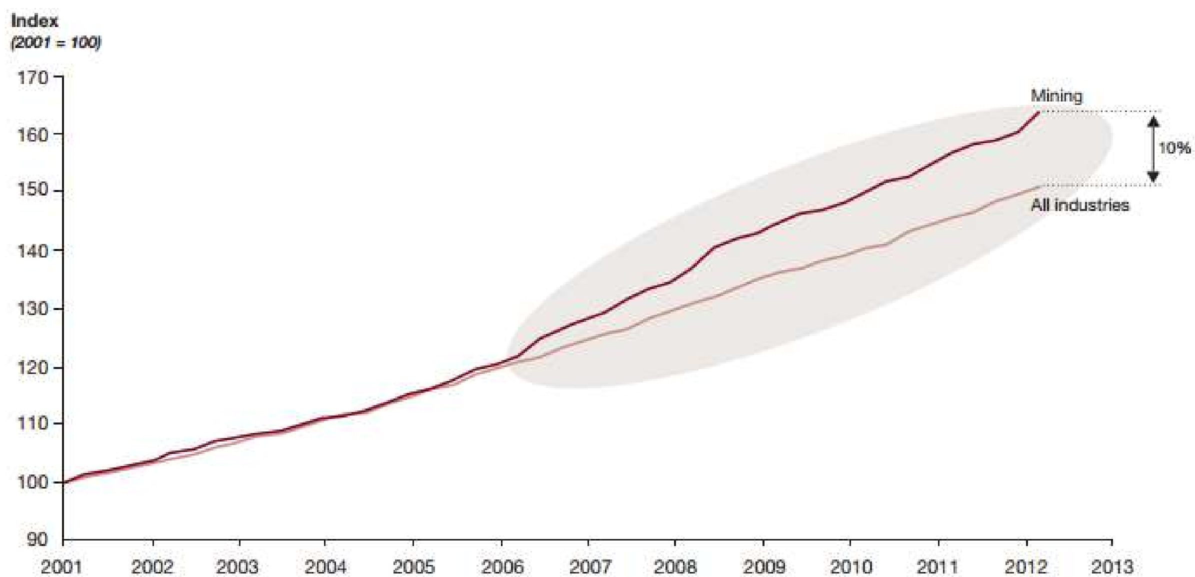
Mudd, 2009

Declining Ore Grades



Mudd, 2009

Increasing Labour Cost



Source: Australian Bureau of Statistics , 2012

Single Side Loading

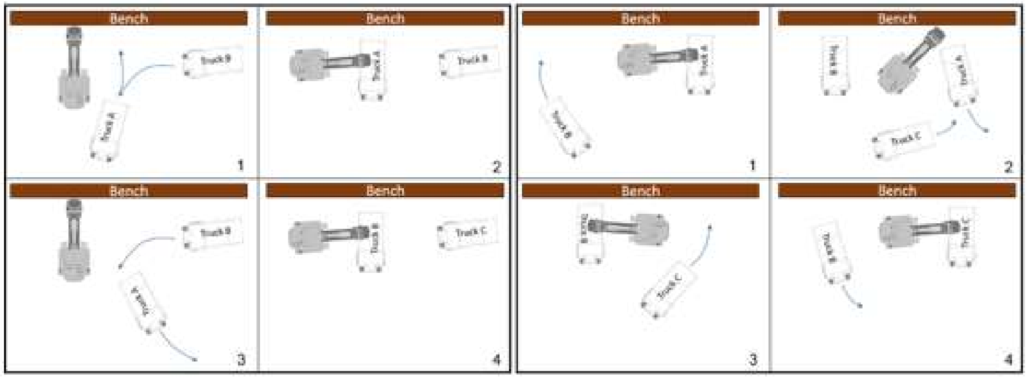


Figure 4-8 Single-side method (left) and double-side method (right)

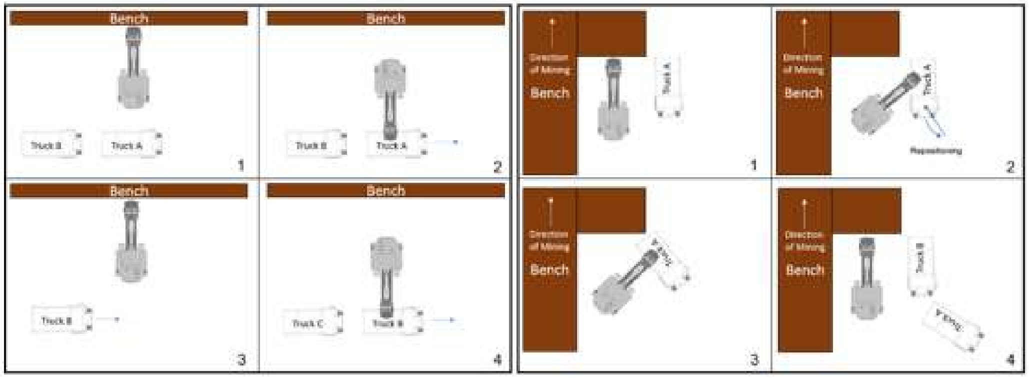


Figure 4-9 Drive-by method (left) and modified drive-by method (right)

Recommendation for further Research

1. Incorporation of the aspects highlighted in the critical discussion
2. Extension of method for heterogeneous truck fleet
3. Extension of method for entire IPCC range
4. Inclusion of multiple periods and Investment cost