Workshop on **SUSTAINABLE P – MANAGEMENT**
CAS , LMU Munich, 10th of June 2016

DEVELOPMENTS AND EFFICIENCY CONSIDERATIONS IN PHOSPHATE ROCK MINING

Bernhard Geissler & Gerald Steiner

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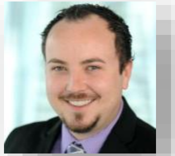

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- **Extended Phosphorus Supply Chain**

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- Methodology & Research Design
  - Economic vs. Resource Efficiency & Applied Data
- Results at the Global and Organizational Level

PART B: Efficiency Performance

- Methodology & Research Design
  - DEA and Economic Efficiency
- Benchmark on Economic Performance

Current Research & Outlook

BACKGROUND OF THIS PRESENTATION

Resources, Conservation and Recycling 105 (2015) 235–245

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Resources, Conservation and Recycling

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Efficiency developments in phosphate rock mining over the last three decades

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Efficiency performance of the world's leading corporations in phosphate rock mining

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INTRODUCTION

- **significance** for **Global Food Security**
  - > 80% of minded phosphate rock (PR) is used for agricultural purposes in form of chemical fertilizers
  - chemical fertilizers account for approximately half of the total crop yield
  - P is not substitutable, nor infinite
- **phosphorus scarcity**
  - claimed peak theory not applicable (dynamics of reserves and resources)
  - no scarcity within the next couple centuries
- **distribution difficulties**
  - China, US and Morocco as major producers
  - 75% of classified reserves (67 GT) are located in Morocco
  - minor reserves in Europe (Russia & Finland)

FACTS & FIGURES

Fig. 3. World PR reserves.

Source: van Kauwenbergh et al. (2013).

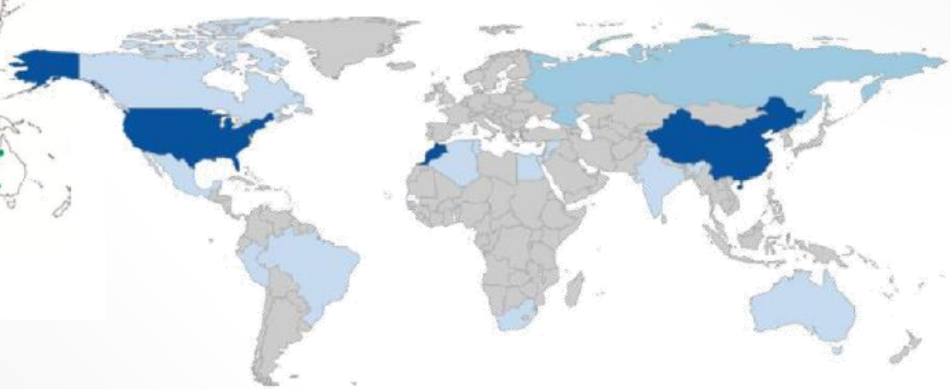


Fig. 2. World PR producing countries.

Source: De Ridder et al. (2012).

data for 2013	Production volume (USGS, 2015)	Reserves (USGS, 2015)
	million metric tons / [share of world production]	million metric tons / [share of world reserves]
Morocco	26.4 [11.73%]	50,000 [74.63%]
China	108 [48%]	3,700 [5.52%]
South Africa	2.3 [1.02%]	1,500 [2.24%]
United States	31.2 [13.87%]	1,100 [1.64%]
Russia	10 [4.44%]	1,300 [1.94%]
Brazil	6 [2.68%]	270 [0.4%]

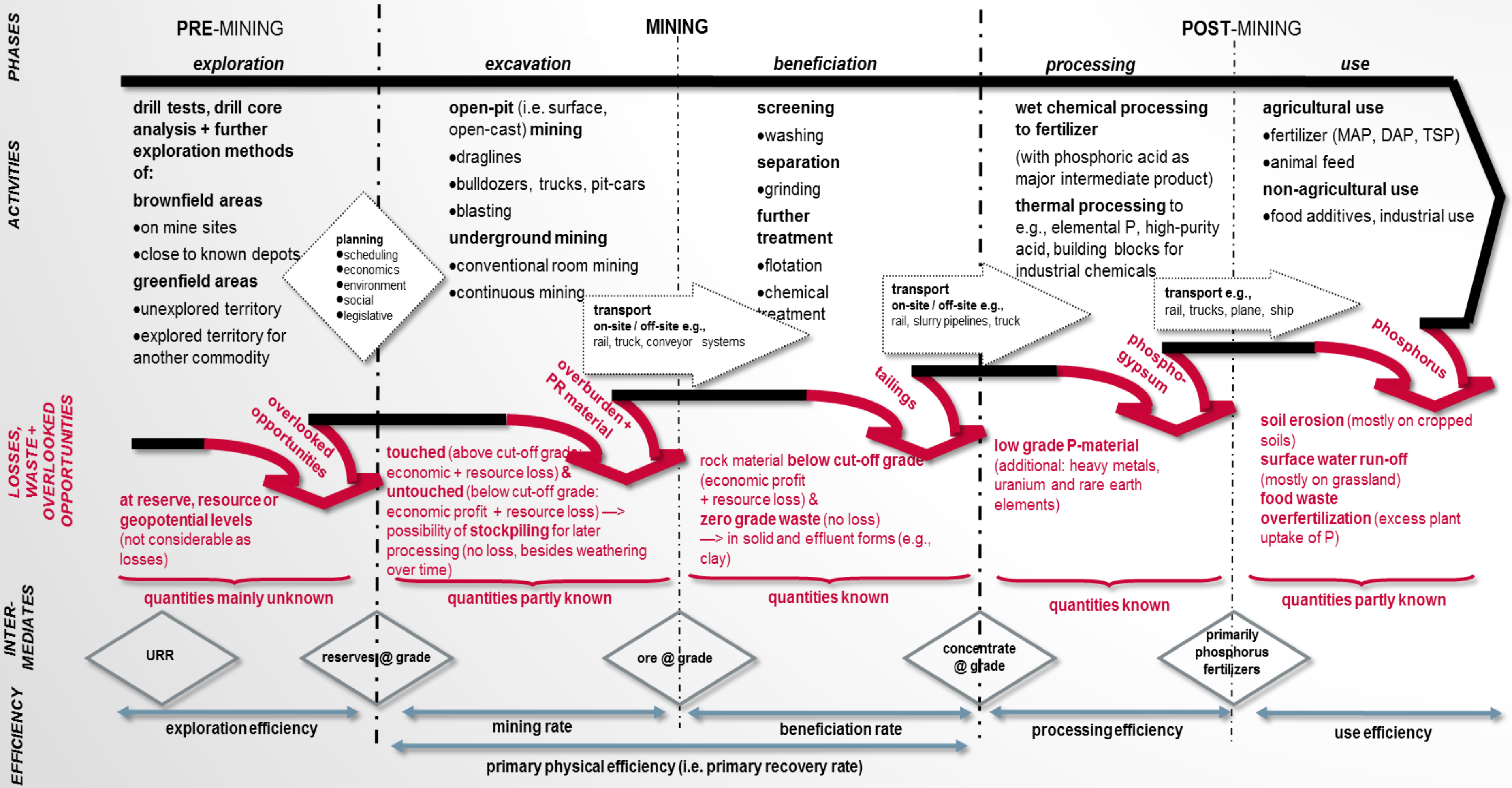
RESEARCH QUESTIONS & ISSUES 1/2

- **efficiency as key in P-mining and -management**
  - efficiency as an output-input ratio is directly related to losses
- **losses are not a static concept**
  - dynamics of technological advances & economic developments
  - what's considered as a loss today might be considered mineable reserve tomorrow (e.g. developments in coper mining)
- **dynamic developments on the global level in 1983 and 2013**
  - external factors triggering developments (e.g., technological, economic, ecological…)
- **developments on the company level**
  - PotashCorp of Saskatchewan, White Springs Mine (Florida) and the Aurora Mine (North Carolina)
  - recovery rates between 1960s to 2009

RESEARCH QUESTIONS & ISSUES 2/2

- **concept and benchmarking of efficiency**
  - efficiency considerations for changing scenarios
- **application of a new research method**
  - introduction of the DEA, to calculate efficiency scores using multiple input and outputs
- **benchmarking of major players in the field**
  - Identification of differences between state-owned and publicly quoted firms

EXTENDED PHOSPHORUS SUPPLY CHAIN



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Current Research & Outlook

ECONOMIC EFFICIENCY

- **large number of parameters** during mining and beneficiation process which **influence economic efficiency**
- **two main reasons** for variation **over time**

  changing deposit characteristics (involuntary) e.g.,
  - change in ore grade and/or other chemical mineral constituents
  - ore depth, layer thickness, physical parameters of ore

  changes made to operational parameters (voluntary)
- **common ratios for varying (volumes) of materials**

1) $$\frac{ore\ mined}{concentrate\ produced}$$

2) $$\frac{ore\ mined + overburden}{concentrate\ produced}$$

3) $$\frac{ore\ mined\ @\ grade}{concentrate\ produced\ @\ grade}$$

RESOURCE RECOVERY & EFFICIENCY

- main goal: **maximize resource recovery whilst minimizing environmental and social impact in its widest sense** e.g.,
  - impact on landscape
  - water resources
  - noise and dust levels…
- **balance** between **economic and resource efficiency** is of **greater importance**
  - recovery of lower grade ores
  - secondary mining of original waste streams
- our focus: **how much of the P in the deposit that we mine ends up in our final product concentrate** (PR-M)
  - ‘real life’ process faced by mining companies
  - decision on cut-off grades and processing

RESEARCH DESIGN & DATA

global level

- mostly **publically not available data**
  - based on two major industry studies from **CRU International** in 2013 and **Fertecon/ Zellars-Williams Inc./ SRI Internaional** in 1983
  - included data: P-ore grade and capacity tonnage as well as comparable grade and tonnage data for the final saleable products after beneficiation
- calculation of **recovery rates in beneficiation** on mine level followed by tonnage-weighted average for **each country** and on a **global basis**

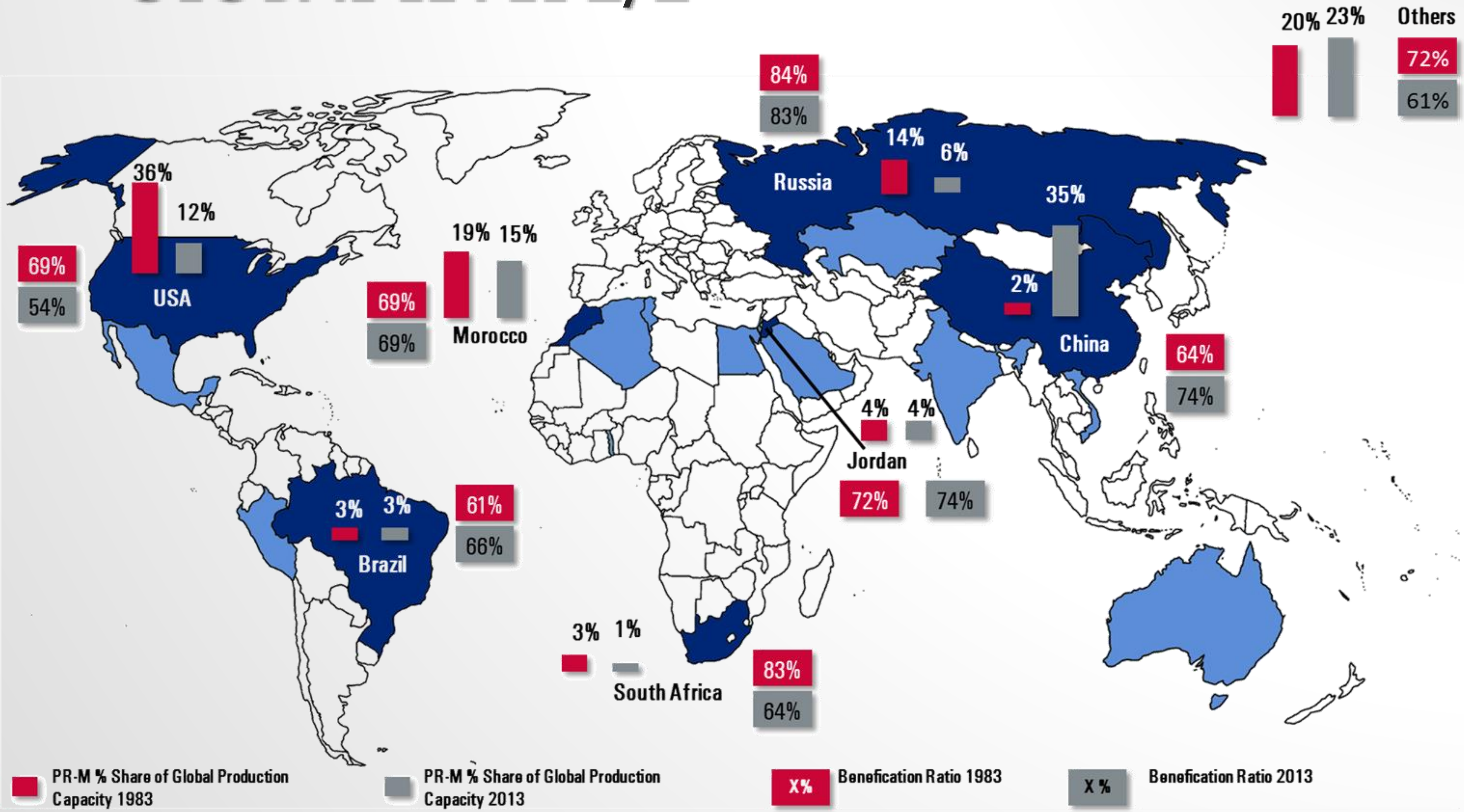
organization level

- Potash Corporation of Saskatchewan (**PCS**)
  - White Springs mine located in Florida, US
  - data extracted from publicly available reports
- **ratio of PR-M volumes to pumped slurry volumes** between 1965 – 2009

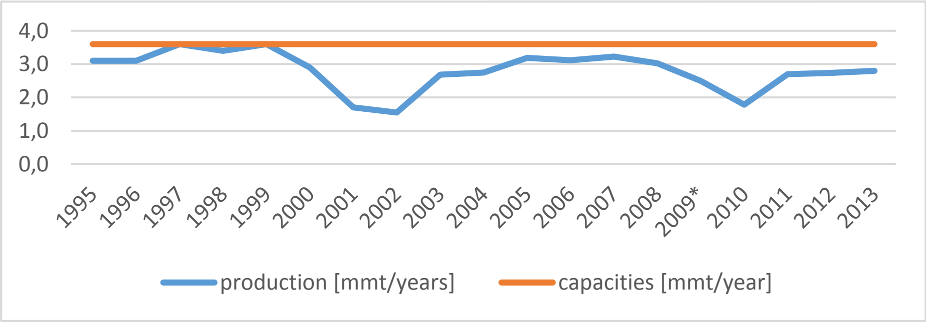
GLOBAL LEVEL 1/2

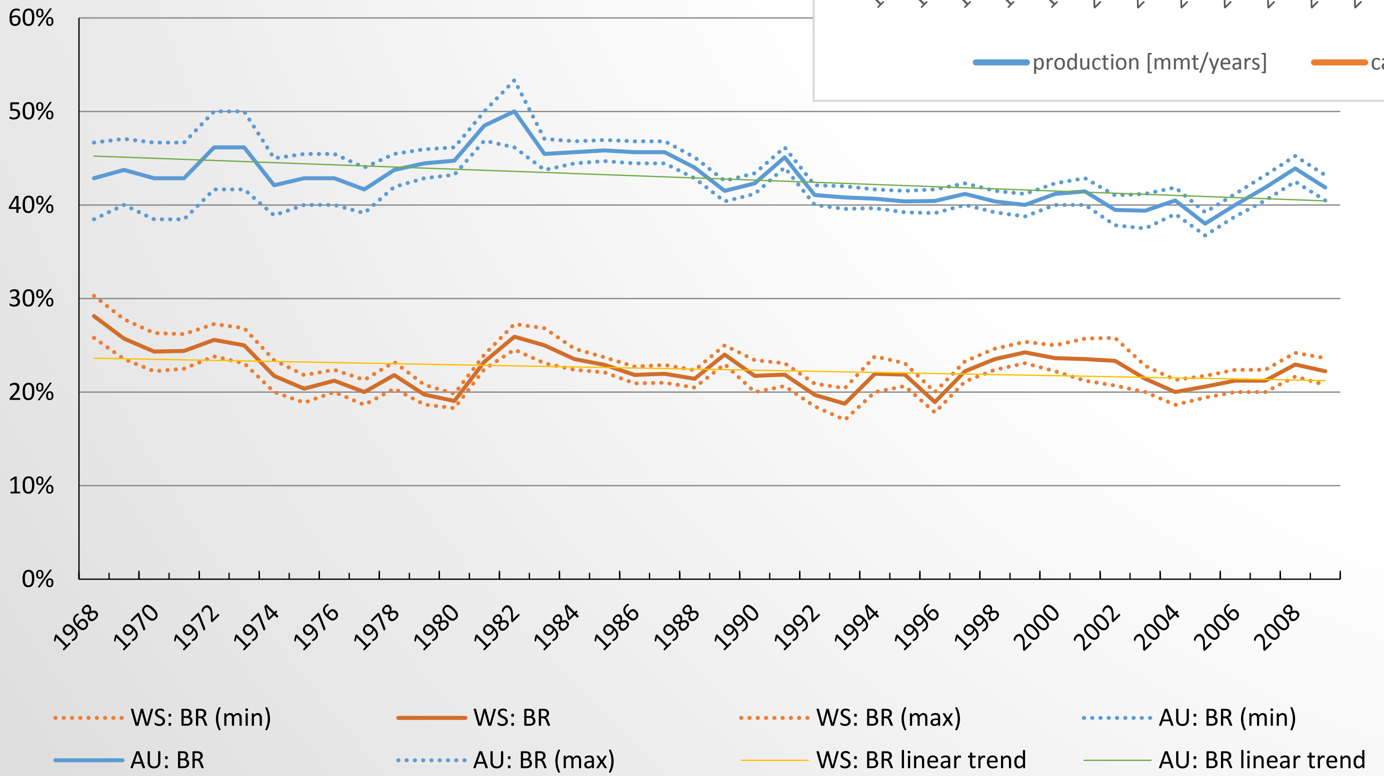
	1983							2013						
	Grades PR-ORE in % P2O5	Volumes PR-ORE in Mt	Grades PR-M in % P2O5	Volumes PR-M in Mt	PR-ORE % Share of Total	PR-M % Share of Total	Beneficiation Rate %	Grades PR-ORE in % P2O5	Volumes PR-ORE in Mt	Grades PR-M in % P2O5	Volumes PR-M in Mt	PR-ORE % Share of Total	PR-M % Share of Total	Beneficiation Rate %
World	14.3	512.7	32.5	161.8	100	100	71.7	17.5	660.7	30.1	257.9	100	100	67.2
Major Producers Sedimentary ore:														
US	11.9	222.7	31.2	58.5	44.4	36.2	68.8	11.8	141.5	29.2	30.9	21.4	12	53.9
China	23.6	6.9	30.4	3.4	1.3	2.1	63.6	21.6	160.3	28.1	91.4	24.3	35.4	74.1
Morocco	27.2	50.9	32.1	29.9	9.9	18.5	69.3	26.4	68.6	31.5	39.3	10.4	15.2	68.5
Jordan	27.5	10.7	32.8	6.5	2.1	4	71.8	25.5	17.3	29.7	11	2.6	4.3	74.3
Mainly igneous ore:														
Russia	11.4	89.7	36.7	23.3	17.5	14.4	83.6	10.1	70.6	38.7	15.3	10.7	5.9	82.8
S Africa	5.9	33.6	36.5	4.5	6.6	2.7	82.9	7.0	26.7	37.3	3.2	4	1.2	63.8
Brazil	9.1	26.4	34.6	4.2	5.1	2.6	60.9	11.1	38.3	35.4	7.9	5.8	3.1	65.8
Others*	19.2	71.8	31.4	31.6	14.0	19.5	71.8	20.8	137.4	29.5	58.9	20.8	22.8	60.9

GLOBAL LEVEL 2/2



ORGANIZATIONAL LEVEL: PCS WHITE SPRINGS MINE AND AURORA MINE





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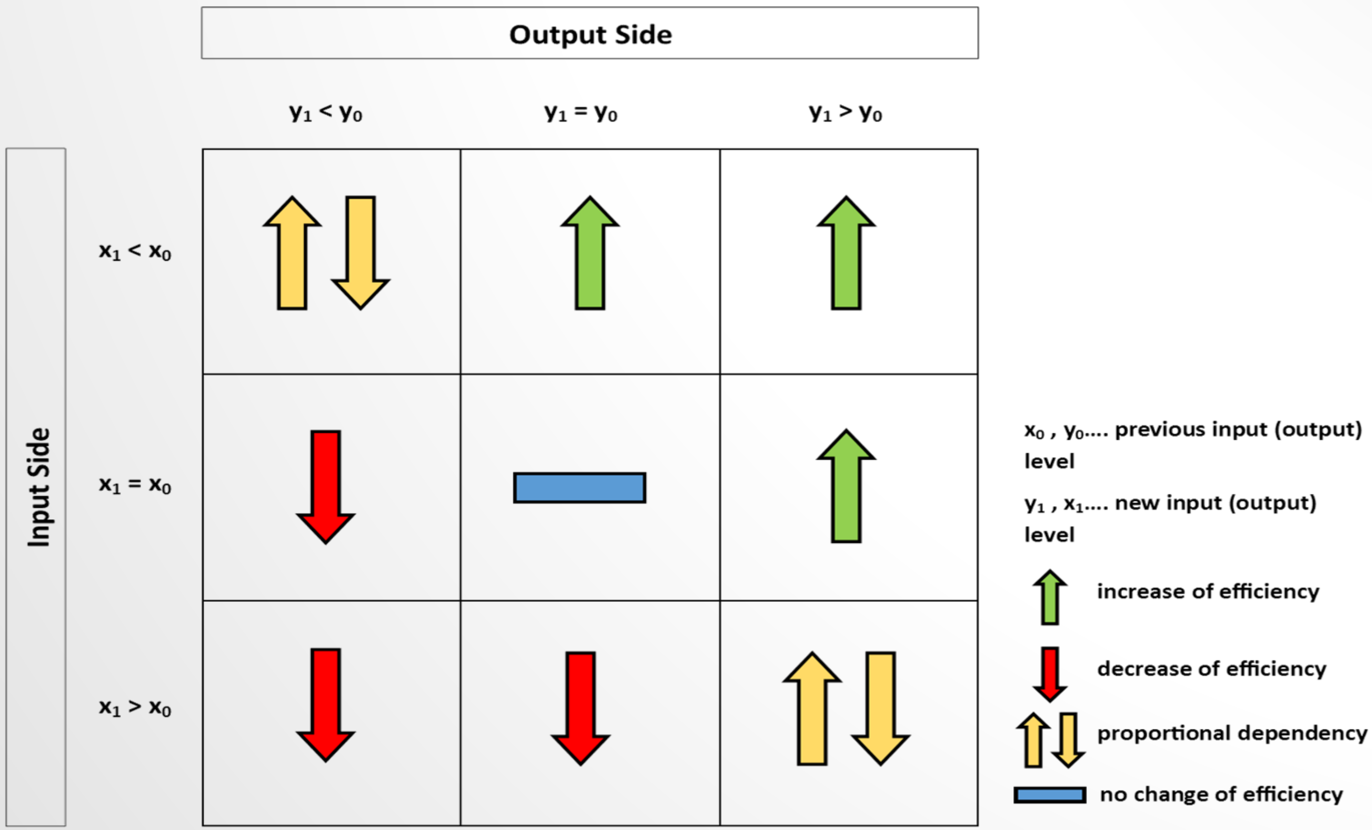
Current Research & Outlook

SIMPLIFIED CHOICES OF A COMPANY



(ECONOMIC) EFFICIENCY - SOME MORE DETAILS

- definitions and explanation
  - **technical efficiency** (Koopmans 1951, p. 60): ". . . an input–output vector is technically efficient if, and only if, increasing any output or decreasing any input is possible only by decreasing some other output or increasing some other input."
  - **allocative efficiency** (Farrell, 1957) is based on the selection of the "right" technically efficient input–output vector under the consideration of given input and output prices
  - **overall productive efficiency** (Farrell 1957)is defined as the product of technical efficiency and allocative efficiency
- all concepts by Farrell assume constant returns to scale (CRS)
- foundation for CCR (Charnes, Cooper, and Rhodes) model in 1978
- later on followed by the BCC (Banker, Charnes, and Cooper) which allowed variable returns to scale (VRS)

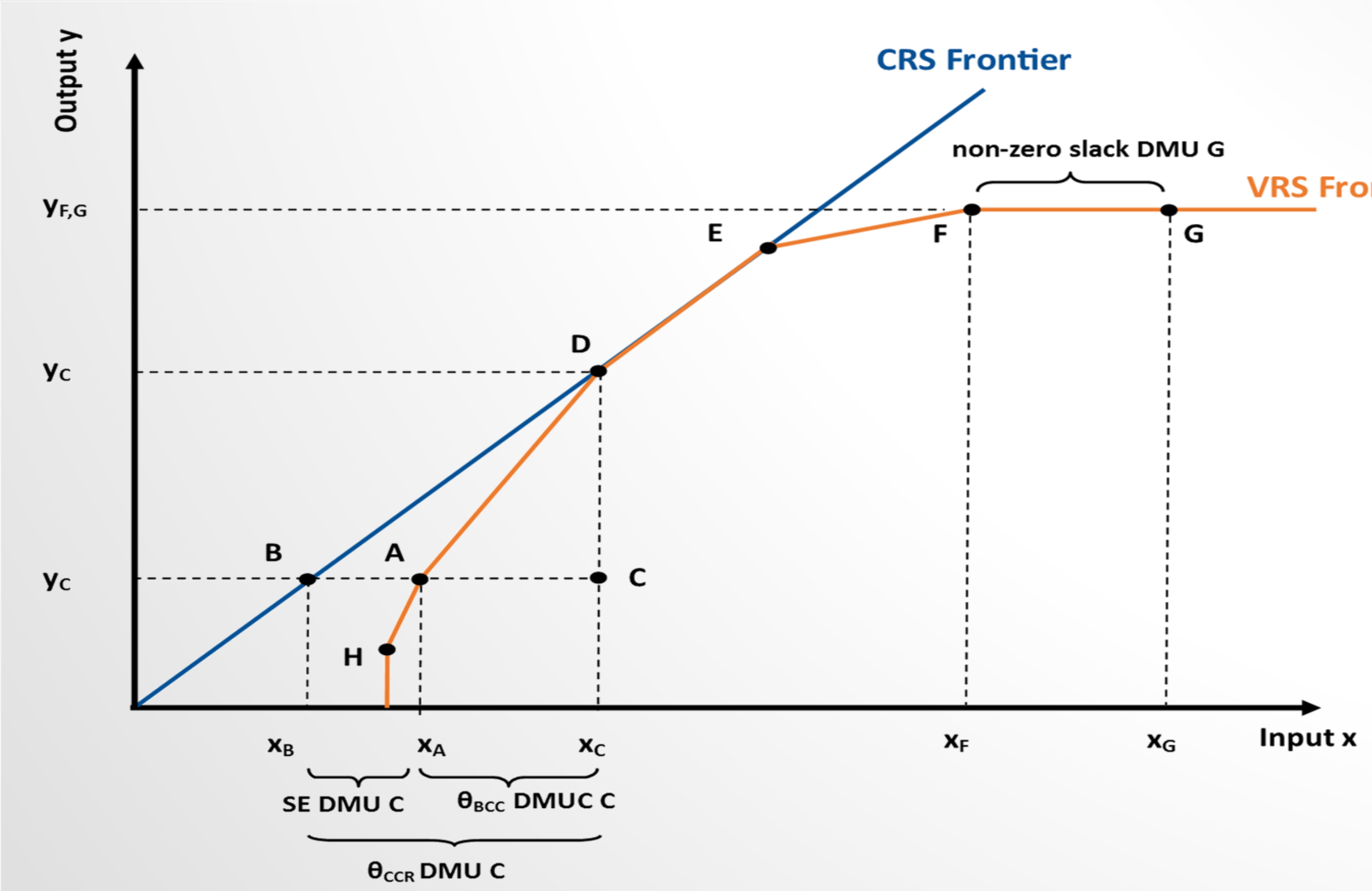
DEA – DATA ENVELOPMENT ANALYSIS 1/3

- data envelopment analysis emerged as a powerful quantitative and analytic tool
- it is used to measure and evaluate the performance of a set of comparable peers, so-called decision-making units
- successfully applied to a broad variety of fields such as banking, health care and hospital efficiencies; military; education and universities; countries; and later to measure environmental performance
- Cooper et al., (2006, p2) characterize the DEA as approach, which "… *does not require the user to prescribe weights to be attached to each input and output, as in the usual index number approaches, and it also does not require prescribing the functional forms that are needed in statistical regression approaches to these topics*".

DEA – DATA ENVELOPMENT ANALYSIS 2/3

- strength of allowing multiple inputs and outputs while calculating efficiency scores und targets
- identification of the the most efficient DMU in the peer set
- calculation of how much inputs have to be decreased (input-oriented) or outputs have to be increased (output-oriented) in order to become as efficient as the best peer in the set

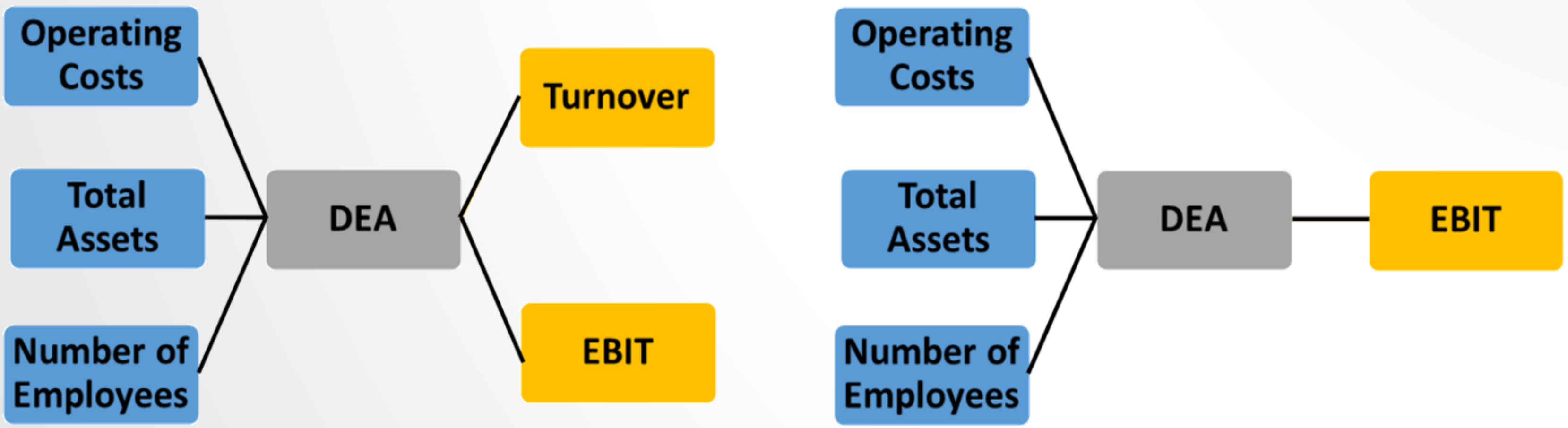
DEA – DATA ENVELOPMENT ANALYSIS 3/3



DATA

- 24 firms operating in phosphate rock mining for which sufficient financial data were available, including the seven largest
- overall global capacities of 661 Mt PR-Ore and 258 Mt PR-M, this study covers 67.3% and 61.4%, respectively
- financial data were obtained from the ORBIS financial database for the year 2012 wherever possible; in single cases, e.g., numbers of employees for some firms, missing data were abstracted from publicly available company reports.
- in the determination of the sample data, the authors selected the respective subsidiary involved in PR mining for which independent reporting was obtainable (e.g., Vale Fertilizantes S.A. instead of the parent company Vale S.A., Anglo American Fosfatos as a subsidiary of Anglo American...
- second dataset is used excluding firms which main business is within other commodities (e.g., Yara or Monsanto)

MODELS



rule of thumb on the number of DMUs (n), number of inputs (m) and number of outputs (s): $n \geq max\{m \times s, 3(m+s)\}$

orientation: input orientation (outputs are kept constant) given the characteristics of a demand market, suggesting not everything produced will get immediately bought

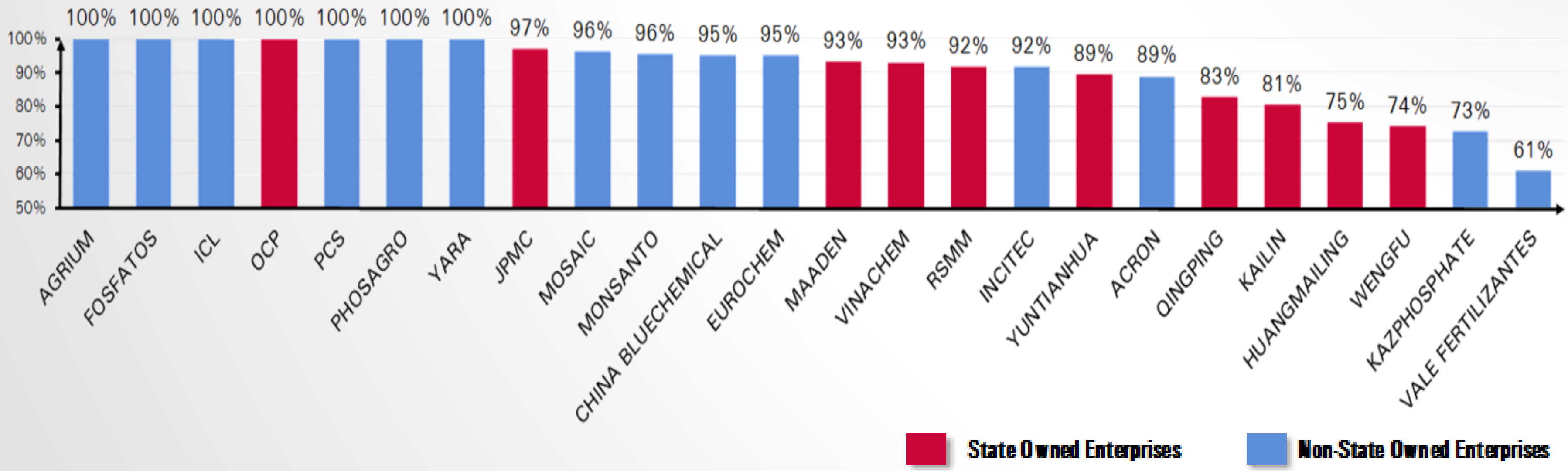
(EXEMPLARILY) RESULTS: SCORES

	Results Model 1				Results Model 2			
	CRS	VRS	SE	RTS	CRS	VRS	SE	RTS
GROUP I – state-owned/ state-controlled								
KAILIN	0.806	0.808	0.997	irs	0.806	0.808	0.997	irs
WENGFU	0.742	0.762	0.973	irs	0.742	0.762	0.973	irs
YUNTIANHUA	0.894	0.953	0.938	drs	0.968	0.969	0.999	irs
QINGPING	0.829	1.000	0.829	irs	0.823	1.000	0.823	irs
HUANGMAILING	0.753	0.820	0.919	irs	0.750	0.816	0.919	irs
GROUP II – publicly quoted								
INCITEC	0.917	0.921	0.997	irs	0.917	0.921	0.997	irs
VALE FERTILIZANTES	0.609	0.612	0.996	irs	0.609	0.612	0.996	irs
FOSFATOS	1.000	1.000	1.000	-	1.000	1.000	1.000	-
PCS	1.000	1.000	1.000	-	1.000	1.000	1.000	-
CHINA BLUECHEMICAL	0.952	0.959	0.993	irs	0.952	0.959	0.993	irs

(EXEMPLARILY) RESULTS: INPUT TARGETS

	Results Model 1			Results Model 2		
	Operation costs	Total assets	Employees	Operation costs	Total assets	Employees
GROUP I – state-owned/ state-controlled						
KAILIN	19.2%	19.2%	19.2%	19.2%	19.2%	19.2%
WENGFU	23.8%	23.8%	23.8%	23.8%	23.8%	23.8%
YUNTIANHUA	8.7%	4.7%	44.5%	8.6%	3.1%	3.1%
QINGPING	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HUANGMAILING	18.0%	18.0%	49.8%	18.4%	18.4%	18.4%
GROUP II – publicly quoted						
INCITEC	7.9%	7.9%	7.9%	7.9%	7.9%	7.9%
VALE FERTILIZANTES	38.8%	68.1%	53.8%	38.8%	68.1%	38.8%
FOSFATOS BRAZIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PCS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHINA BLUECHEMICAL	4.1%	4.1%	4.1%	4.1%	4.1%	4.1%

OVERALL RESULTS



CONCLUSION: **“The frequencies of efficiency performance do not differ in such a way that a Fisher Exact Test would suggest statistical significance for these data. This indicates that general assumptions regarding the different strategies of state-owned and publicly quoted firms are not necessarily valid.”**

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Current Research & Outlook

OUTLOOK

- **follow-up publications towards sustainable p management with a focus on mining**
  - inclusion of further dimensions (e.g., social, environmental, policy…)
  - identification of drivers for efficiency
  - application of further systemic methods and system simulation
  - price model to incorporate prices as a determining dynamic factor simulation models
- **knowledge extension**
  - cross-boundary collaborations in mining networks for efficiency improvements and innovation
  - policy implications for resource management and global food security

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DEA – DATA ENVELOPMENT ANALYSIS 3/3

1) $$\theta^* = \min \theta$$

subjected to:

2) $$\sum_{j=1}^{n} x_{ij}\lambda_j \leq \theta x_{i0} \quad (i = 1, \dots, m)$$

3) $$\sum_{j=1}^{n} y_{rj}\,\lambda_j \geq y_{r0} \quad (r = 1, \dots, s)$$

4) $$\sum_{j=1}^{n} \lambda_j = 1$$

5) $$\lambda_j \geq 0$$

6) $$max \sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+$$

subjected to:

7) $$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta^*\, x_{i0} \quad (i = 1, \dots, m)$$

8) $$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{r0} \quad (r = 1, \dots, s)$$

9) $$\sum_{j=1}^{n} \lambda_j = 1$$

10) $$\lambda_j, s_i^-, s_r^+ \geq 0\ \forall\, i, j, r$$