SAIMM
THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

University of the Witwatersrand

9th International PGM Conference 2025
27-28 October 2025, Sun City, Rustenburg, South Africa

A FRAMEWORK FOR TECHNOLOGY SELECTION IN LARGE SCALE SYSTEMS:

Case study of mining technology selection in PGM Mining applying system dynamics modelling

By

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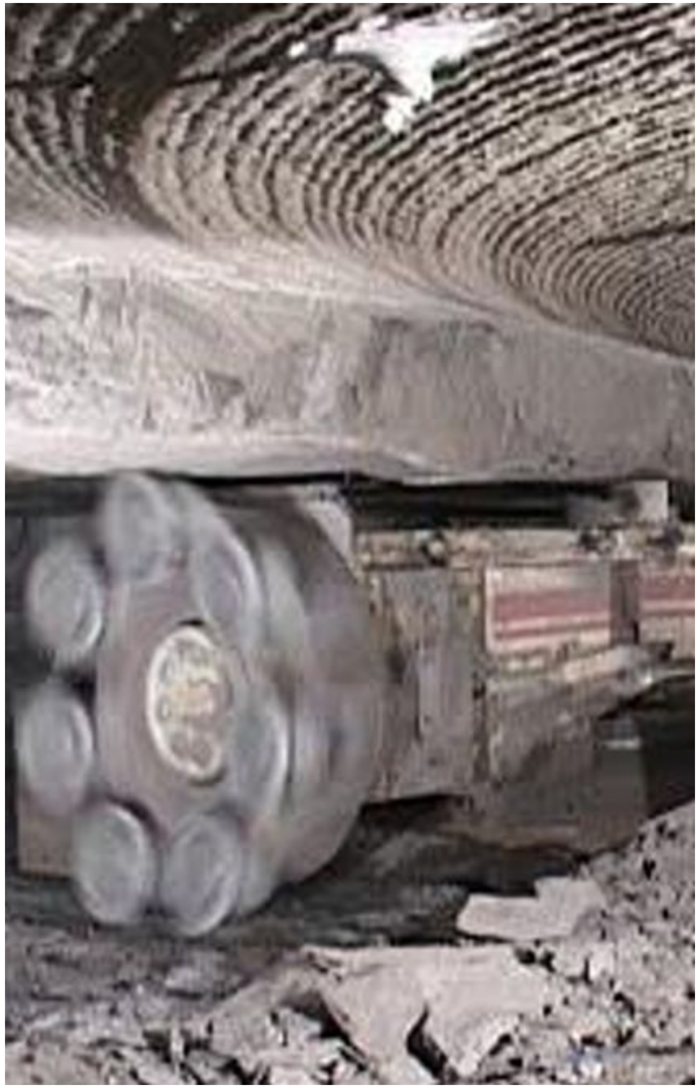
Introduction



Picture Sources – Sandvik (Smit,2014)

Literature Review – Economics of technology

The two main inputs to production are Capital (precisely physical capital such as machines) and labour.

In neo-classical economics, the technology available for converting capital and labour into output is summarised by the ***PRODUCTION FUNCTION.***

The most used function is the Cobb–Douglas Production (CDP) Function (Cottrell, 2019; Cobb & Douglas, 1928) with the following form representing relationship between labour and capital:

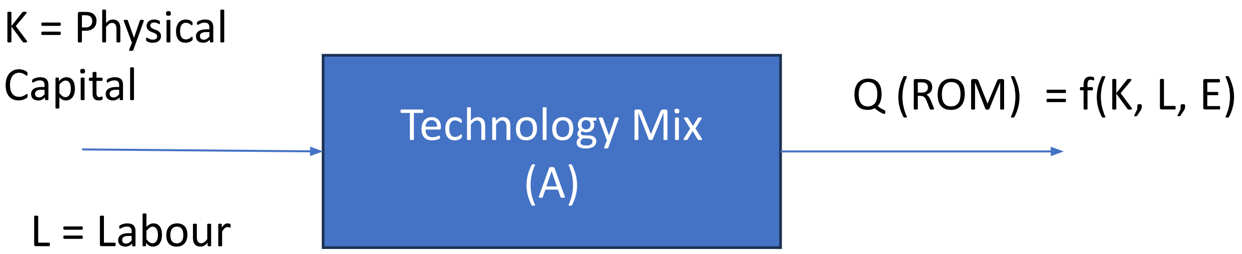
$$Q = f(K, L) = AK^{\alpha}L^{\beta}, \text{ where } \alpha + \beta = 1$$

Where
Q = Aggregate output;
K = the capital input and represents the total investment in fixed assets
L = the labour inputs which is the total number of persons or hours worked in a year.
A = Positive constant which means total factor productivity – qualitative factor of the technology.
Parameters a and β show the output elasticities to capital and labour, respectively.

(Clinton, 2004; Başeğmez, 2021; Lowe, 1995)

The mining technology mix

"Technology = the feasible means of converting inputs into outputs"



90% of PGM mining is underground. This is due to the geology of the ore bodies.

Different technology mixes are applied depending on the nature of the orebody

1. Conventional mining
2. Mechanized mining
3. Continuous hard rock cutting

Types of Orebody affects the mining method

- ❑ Merensky
- ❑ UG2
- ❑ Others

Problem statement

Traditional econometric methods uses statistical regression analysis methods to define key parameters of the production function.

AIM OF PAPER

Demonstrate **systems dynamic modelling** techniques to determine technology factors on the output – focus on platinum underground mining systems.

Central Research Question

How do we select technology in a mining system considering the long-term nature of mining projects and the inherent uncertainties in the mining industry such as commodity pricing

Research Sub-Questions (THE ECONOMICS OF TECHNOLOGY DECISIONS)

1. How do we model a dynamic PGM mining system, and
2. How do we apply systems dynamic modelling tools for technology decision making

Literature Review- Technology and production function

Figure 1 - Capital Intensive vs Labour Intensive

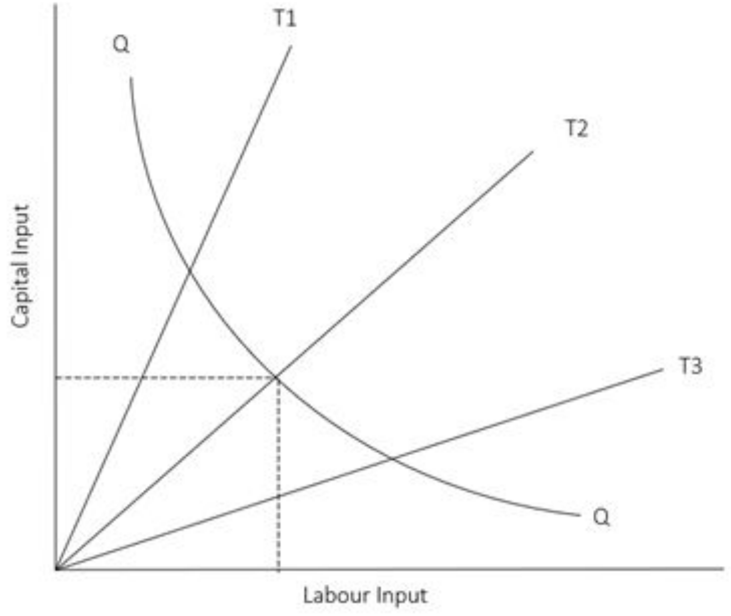


Figure 2 - Efficiency improvement on a given technology

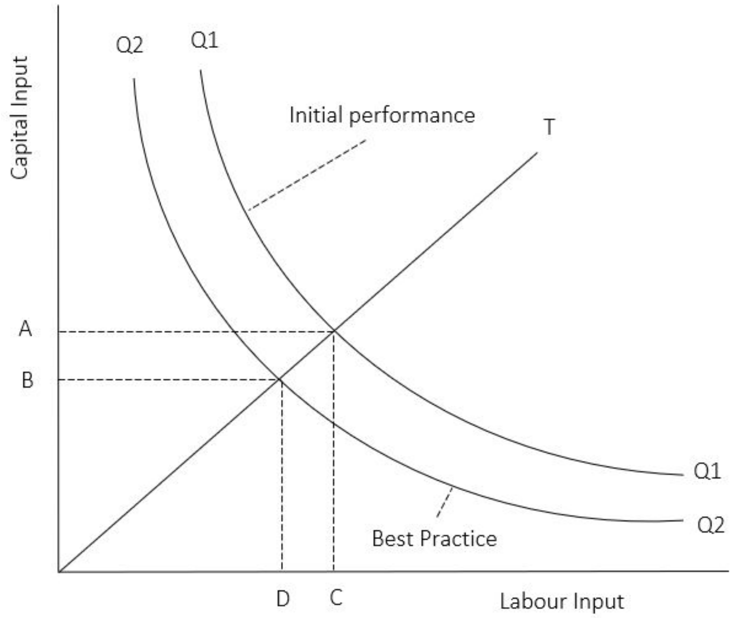
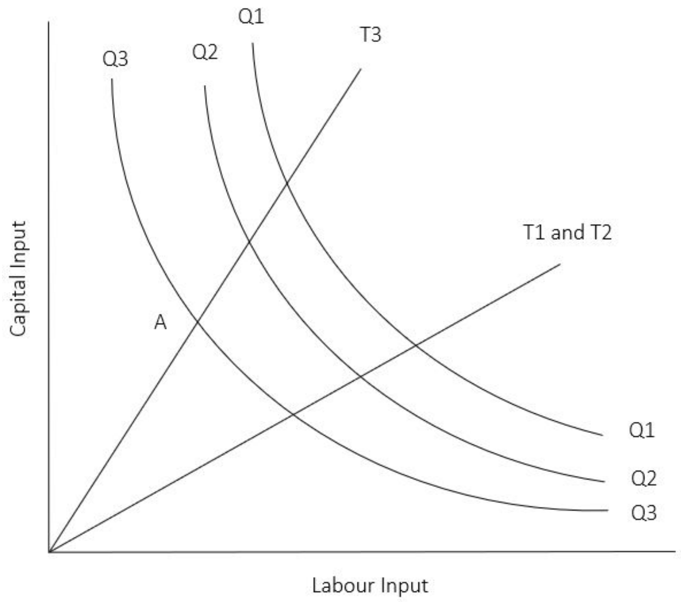


Figure 3 - Technology Change



- ***Figure1*** represents, T1 = capital intensive technology, such as full automation, T2 = an intermediate technology and T3 = labour intensive operation, with little technology (Lowe,1995)
- ***Figure 2*** shows the effect of production efficiency improvement with a given technology. Improvements in output, Q can be attained by better deployment of staff, more effective equipment utilization, greater reliability, minor technical refinements, etc. (Lowe, 1995). As a result, the same output can be achieved with reduced capital and labour inputs. The effect is shown by a move from line Q1Q1 to line Q2Q2 (Lowe,1995).
- ***Figure 3*** is biased technology change expressed by line Q3Q3 representing a different mix of labour and capital inputs. The nature of bias or direction of technology change should be noted. Example is the installation of an automated production line which is capital intensive with a high degree of embodied technology. The labour content of production is correspondingly reduced (Lowe, 1995).

Literature Review- when to make an investment decision

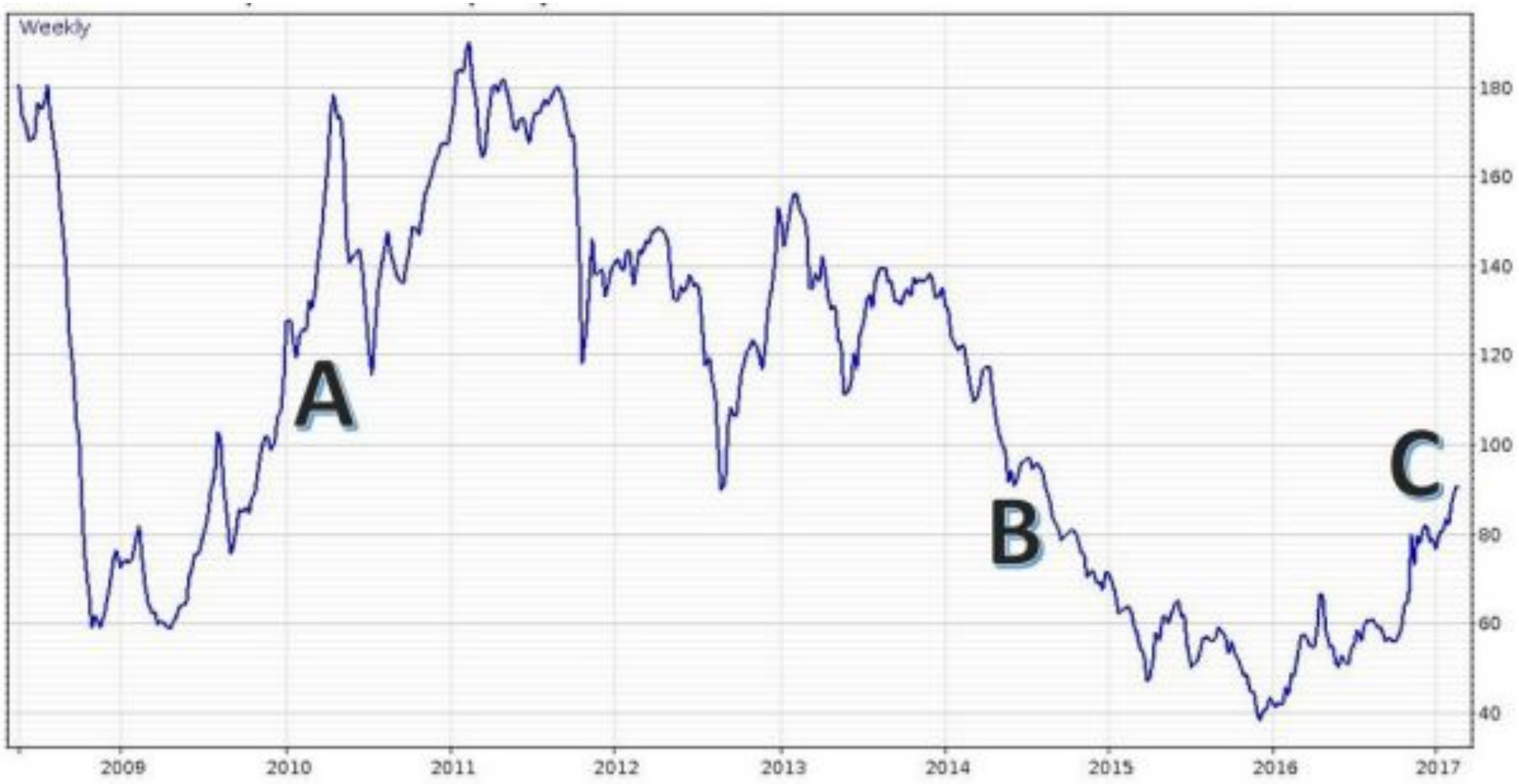
Technological decisions and improvements in mining are largely driven by the commodity cycles.

"Commodity demand and price cycles influences to a large extend the way mining leaders make decisions in the various periods whether ro invest in technology or not" Runge (2017)

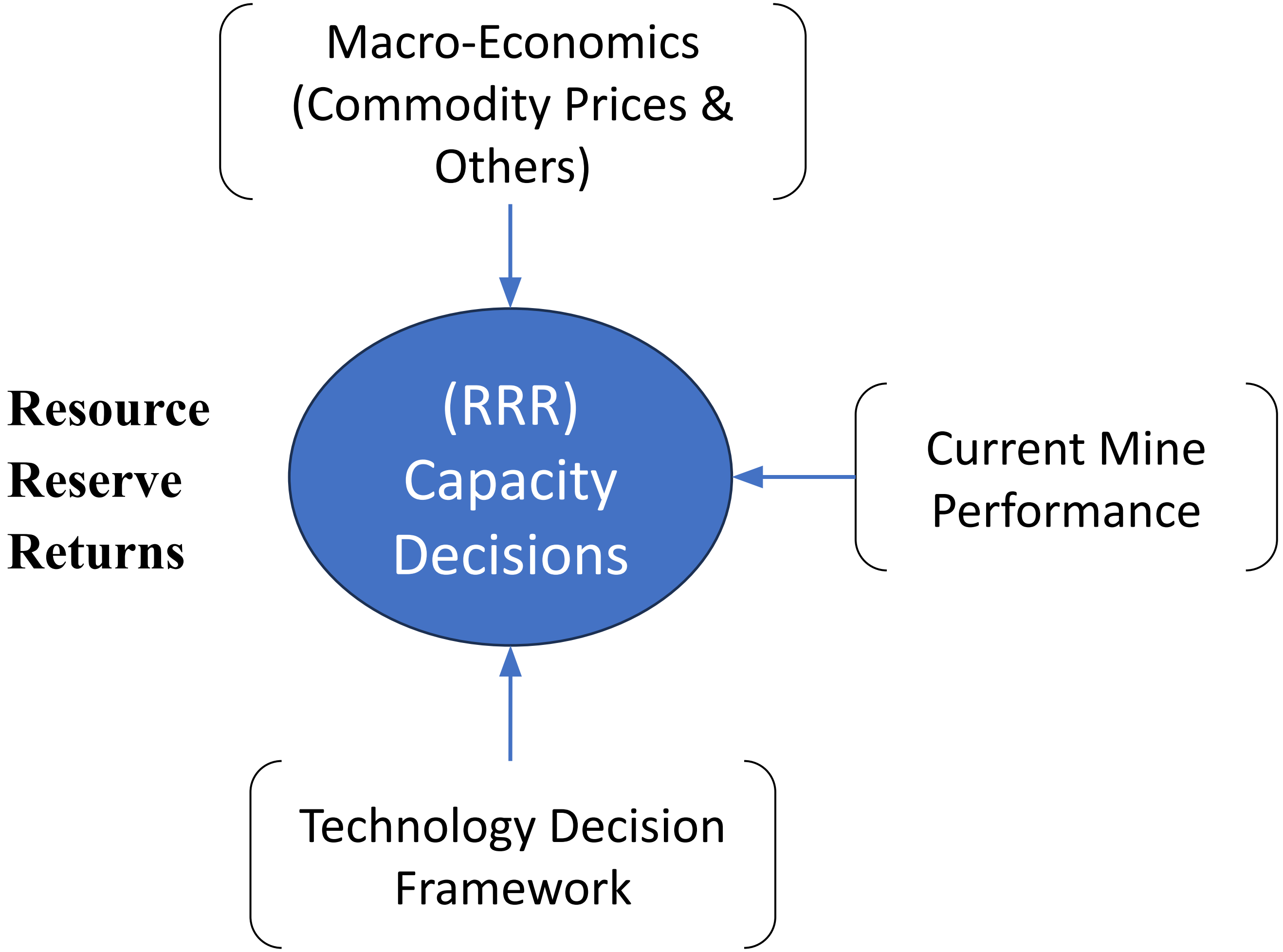
Phase A – Boom maximise production at all costs, Capital expenditure and little focus on efficiencies

Phase B – Down turn. Reducing costs, stop exploration and reduce development

Phase C – Upturn and stability. Technological investments justified to bring much needed savings and operational improvements. Little appetite for capital expenditure hence the need to do technological improvements which bring savings.



Model formulation – Mine economic model

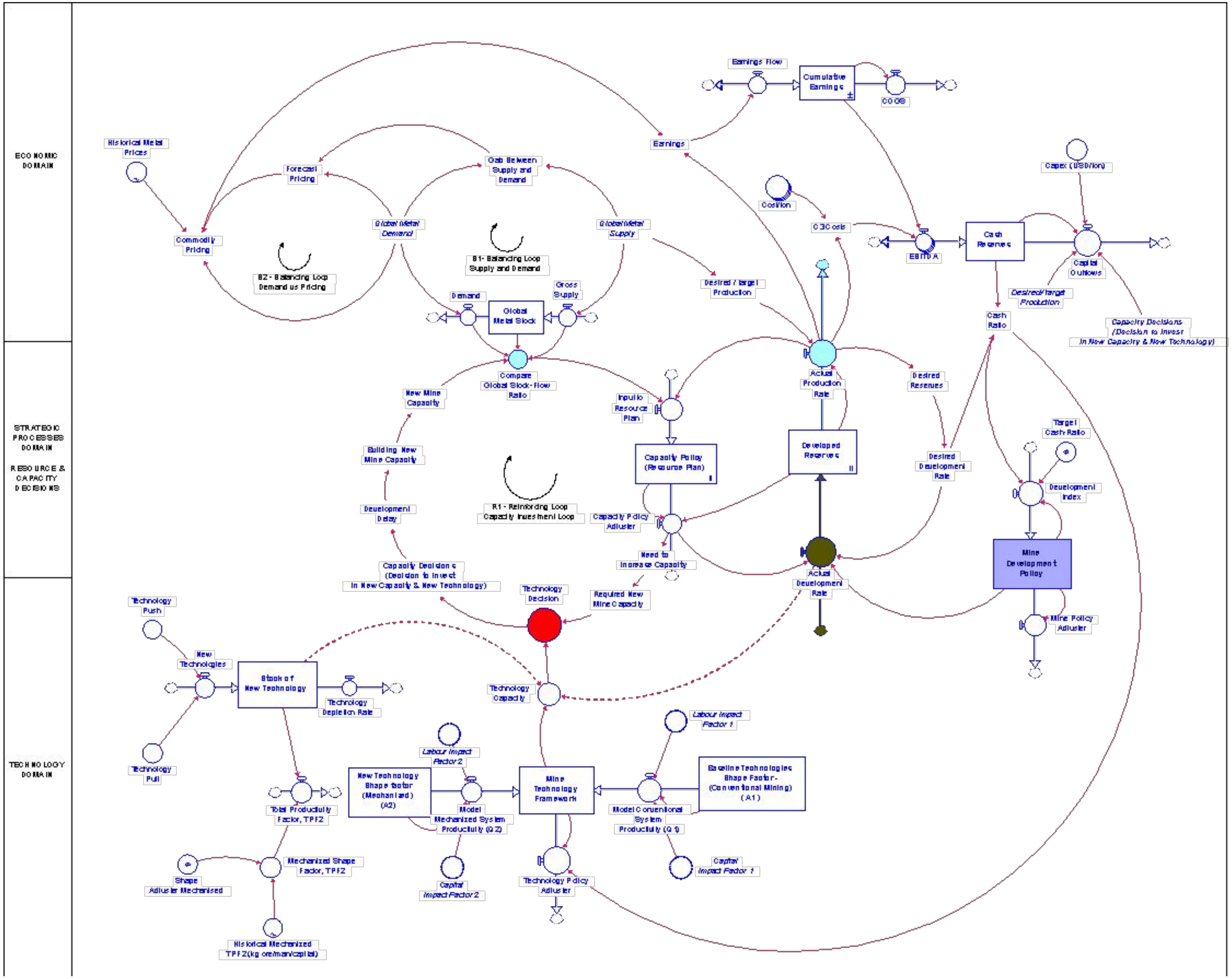


Mining Economic Model

Policy Structure Diagram linking the dynamic interaction

FEEDBACK LOOPS

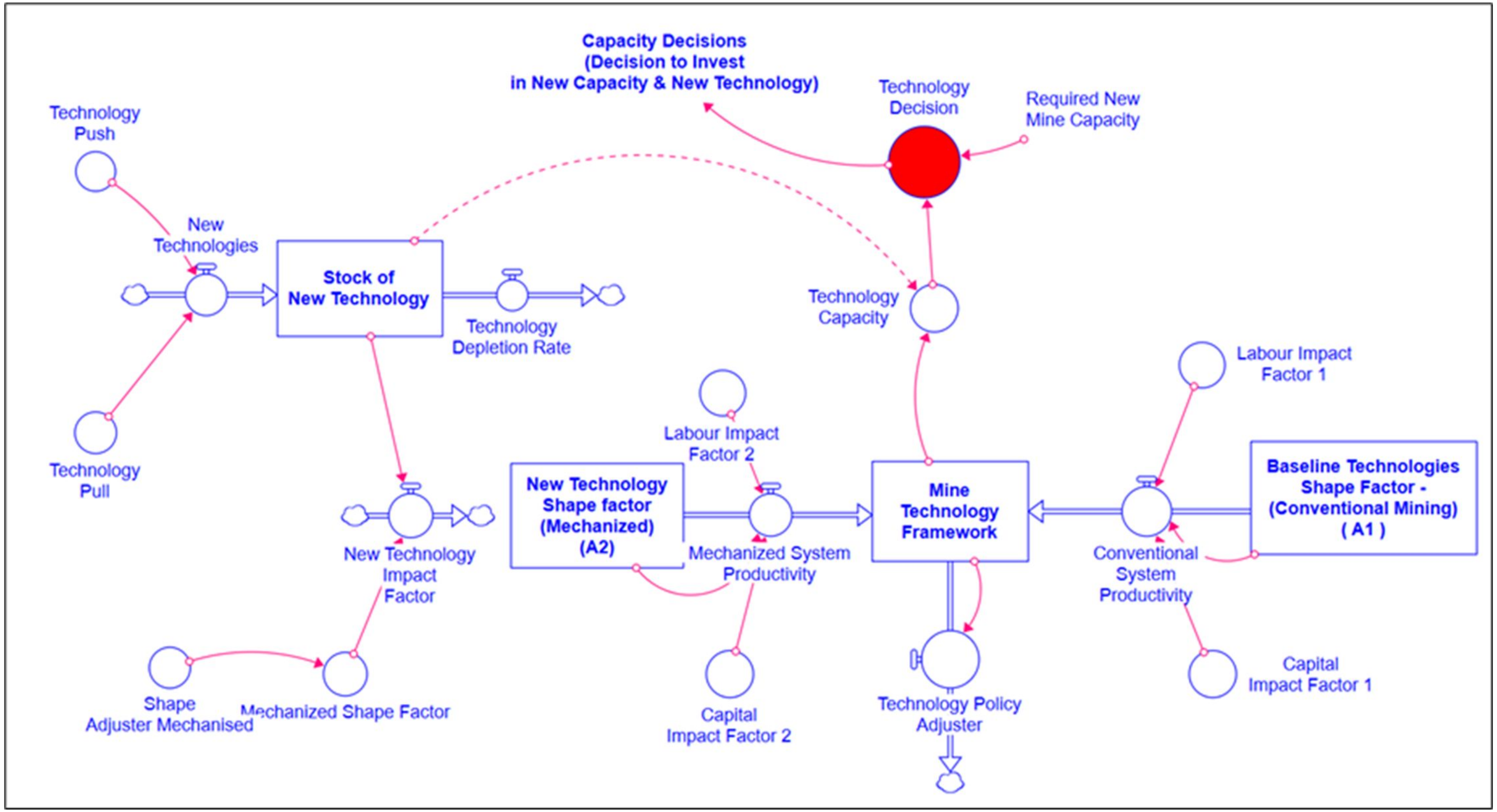
- Commodity markets dynamics loops
- Capacity planning / Resources and Reserves (long term) mine planning loop
- Returns (EBIDTA, ROI, NPV, IRR)
- Technology Framework


ECONOMIC DOMAIN
STRATEGIC PROCESSES DOMAIN
RESOURCE & CAPACITY DECISIONS
TECHNOLOGY DOMAIN
Historical Metal Prices
Commodity Pricing
Forecast Pricing
Gap Between Supply and Demand
Global Metal Demand
Global Metal Supply
B2 - Balancing Loop Demand vs Pricing
B1 - Balancing Loop Supply and Demand
Demand
Global Metal Stock
Gross Supply
Compare Global Stock-Flow Ratio
Earnings Flow
Cumulative Earnings
COGS
Earnings
Cost/ton
C3 Costs
EBITDA
Cash Reserves
Capex (USD/ton)
Capital Outflows
Desired/Target Production
Capacity Decisions (Decision to Invest In New Capacity & New Technology)
Cash Ratio
Desired / Target Production
Actual Production Rate
Desired Reserves
Developed Reserves
Input to Resource Plan
Capacity Policy (Resource Plan)
Capacity Policy Adjuster
Need to Increase Capacity
Required New Mine Capacity
Desired Development Rate
Actual Development Rate
Target Cash Ratio
Development Index
Mine Development Policy
Mine Policy Adjuster
New Mine Capacity
Building New Mine Capacity
Development Delay
R1 - Reinforcing Loop Capacity Investment Loop
Capacity Decisions (Decision to Invest In New Capacity & New Technology)
Technology Decision
Technology Push
New Technologies
Stock of New Technology
Technology Depletion Rate
Technology Pull
Technology Capacity
Total Productivity Factor, TPF2
Shape Adjuster Mechanised
Mechanized Shape Factor, TPF2
Historical Mechanized TPF2(kg ore/man/capital)
New Technology Shape factor (Mechanized) (A2)
Labour Impact Factor 2
Model Mechanized System Productivity (Q2)
Capital Impact Factor 2
Mine Technology Framework
Technology Policy Adjuster
Labour Impact Factor 1
Model Conventional System Productivity (Q1)
Baseline Technologies Shape Factor - (Conventional Mining) (A1)
Capital Impact Factor 1

Sub model – Technology Decision Making

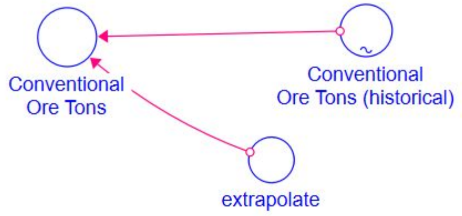
Analysis of the technology domain

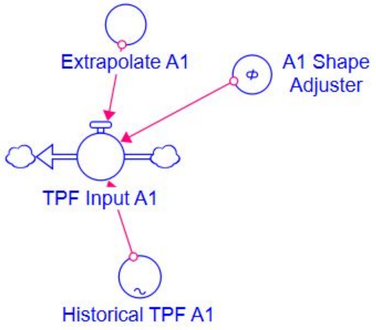
- mechanized technologies versus conventional technologies
- Determine the total productivity factor (A) of the different technologies amid the variations in capital and labour

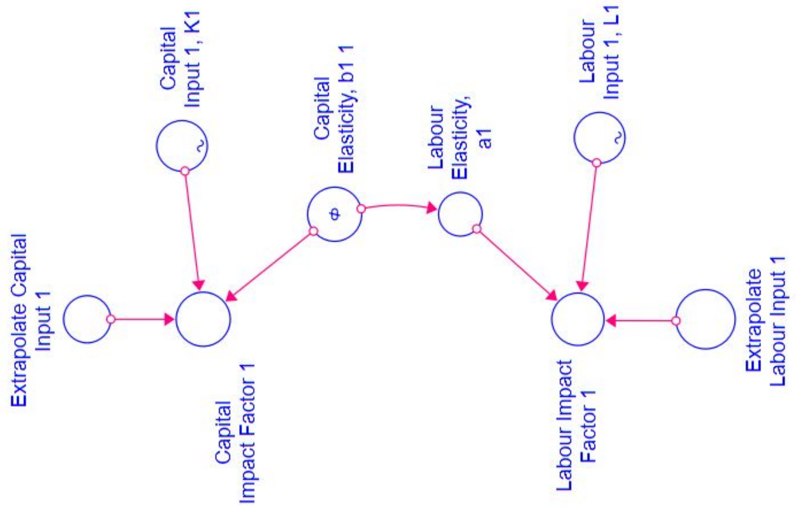


Sub model – Parameters

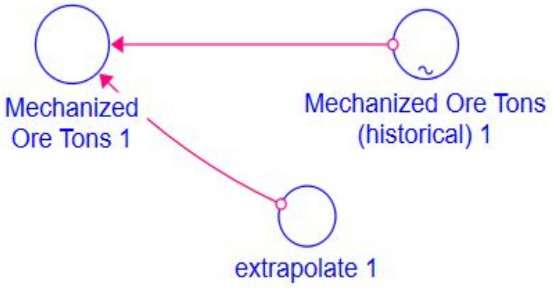
Conventional system analysis: Model simulation of conventional mining factors

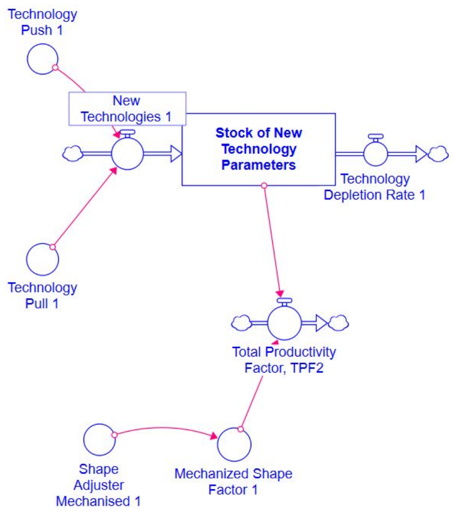


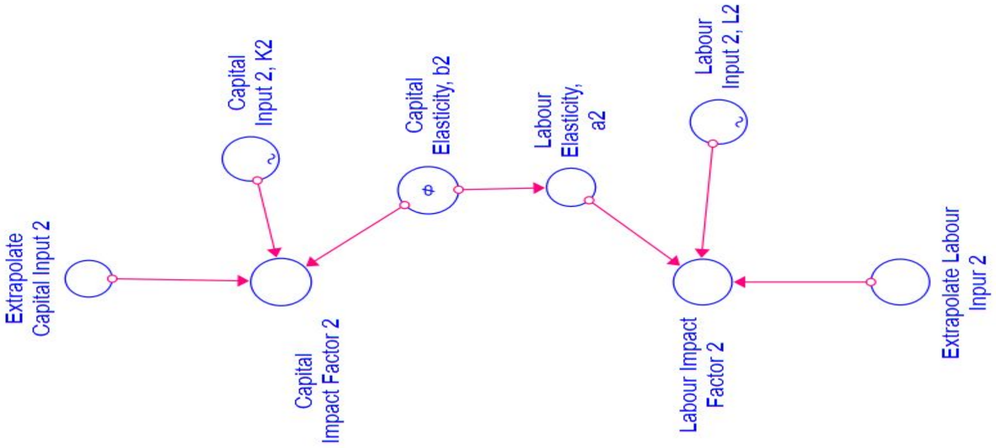




Mechanised system analysis: Model simulation of mechanized system







Data

- Data was obtained from public disclosure data (annual reports) of major platinum mining entities over a period of 9 years from year 2011 to 2020. Data from four underground mining operations was analysed in this study.

- Output (Q) Represents the aggregated output from the underground (ROM)

- Capital (K) represents the physical capital which is represented by the equipment depreciation and maintenance inputs.

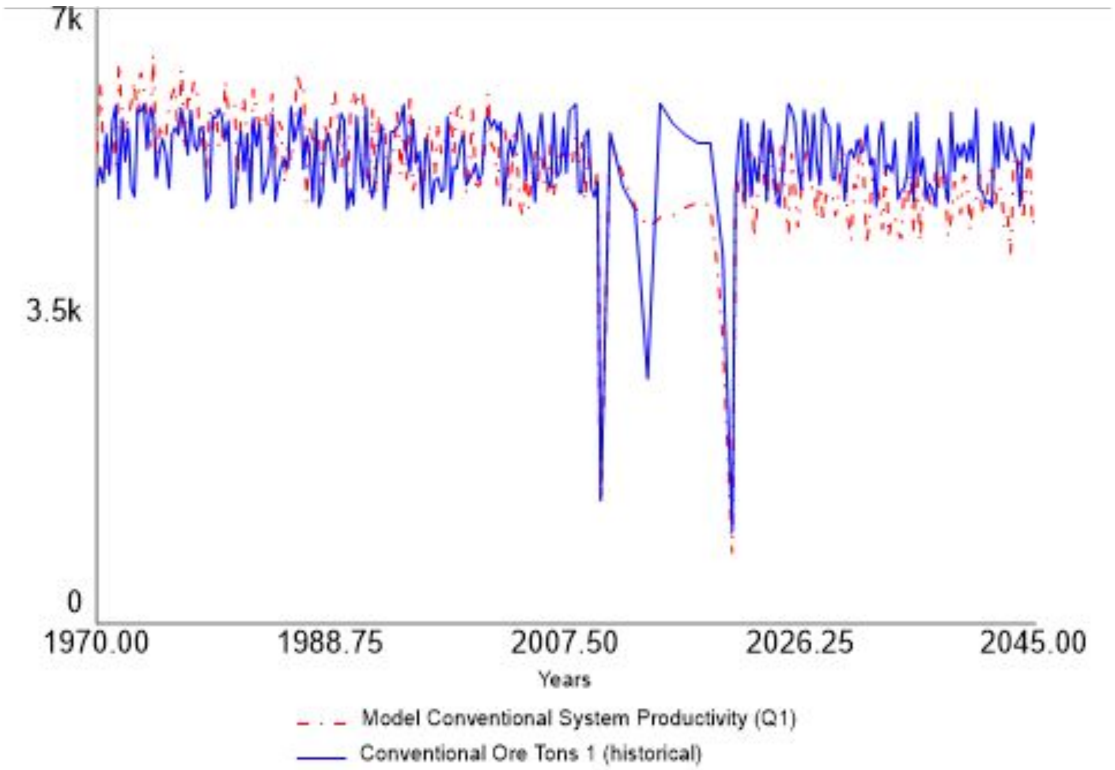
- Labour (L) variable is the total number of people engaged by the mining production entity. The quality of labour was assumed to be the same across all the mining entities, but this may not be true due to different skills levels and other social factors can impact the overall labour and capital (technology) productivity.

Table 1. Descriptive Statistics (2011 - 2020)

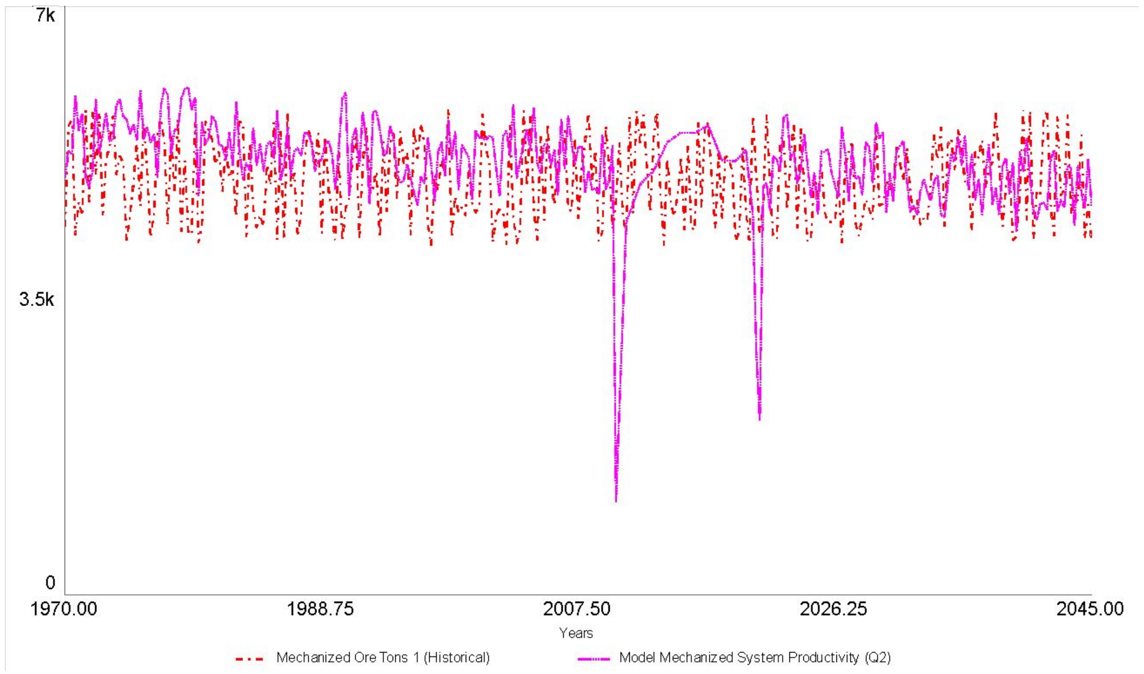
	Conventional Mining System			Mechanized Mining System		
Variable	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Produced Ore Tons	5,421	4,702	5,917	5,063	4,153	5,775
Capital Input, K (USD million)	70	54	110	61	42	78
Labour Input, L (No of employees)	14,942	13,970	15,945	7,268	6,716	7,793

Results

- Conventional mining system modelling result – mapping of model data versus historical data



- Mechanised mining system modelling result – mapping of model data versus historical data



Results

❑ Conventional mining system model result – mapping of model data versus historical data

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Conventional Ore Tons 1 (historical)	5.59k	4.98k	4.7k	2.78k	5.92k	5.69k	5.56k	5.47k	5.47k	4.19k
Model Conventional System Productivity (Q1)	5.5k	5.12k	4.74k	4.51k	4.62k	4.64k	4.73k	4.79k	4.76k	3.2k
Historical TPF A1 (kg ore/man/capital)	3.6	3.9	4.7	3.3	6.8	6.6	6.5	6	6.1	16.8
Baseline Technologies Shape Factor - (Conventional Mining) (A1)	1.68M	1.67M	1.67M	1.66M	1.66M	1.65M	1.65M	1.64M	1.64M	1.63M
Capital Input 1, K1	110	90	71	59	60	57	54	57	57	16
Capital Impact Factor 1	4.12	3.88	3.61	3.42	3.44	3.38	3.33	3.38	3.38	2.31
Capital Elasticity, a1	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301
Labour Input 1, L1	14.2k	14k	14k	14.1k	14.6k	15.1k	15.9k	15.9k	15.8k	15.6k
Labour Impact Factor 1	795	788	786	793	811	829	862	861	858	850
Labour Elasticity, b1	0.699	0.699	0.699	0.699	0.699	0.699	0.699	0.699	0.699	0.699

Results

- Mechanised mining system model result – mapping of model data versus historical data

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Mechanized Ore Tons 2 (Historical)	4.27k	5.38k	5.42k	5.19k	5.22k	4.34k	5.6k	4.48k	4.21k	4.22k
Model Mechanized System Productivity (Q2)	4.43k	4.88k	5.04k	5.38k	5.5k	5.5k	5.58k	5.17k	5.16k	4.9k
Historical Mechanized TPF2 (kg ore/man/capital)	85	69	43	37	35	36	38	46	45	33
New Technology Shape factor (Mechanized) (A2)	2.88M	2.88M	2.87M	2.87M	2.86M	2.86M	2.85M	2.85M	2.84M	2.84M
Capital Input 2, K2	42	52	55	57	63	69	78	62	63	65
Capital Impact Factor 2	2.96	3.15	3.21	3.24	3.33	3.42	3.55	3.32	3.33	3.1
Capital Elasticity, a2	0.291	0.291	0.291	0.291	0.291	0.291	0.291	0.291	0.291	0.291
Labour Input 2, L2	6.72k	7.07k	7.26k	7.86k	7.79k	7.52k	7.33k	7.26k	7.2k	7.46k
Labour Impact Factor 2	518	537	548	579	576	562	551	548	545	558
Labour Elasticity, b2	0.709	0.709	0.709	0.709	0.709	0.709	0.709	0.709	0.709	0.709

Summary findings

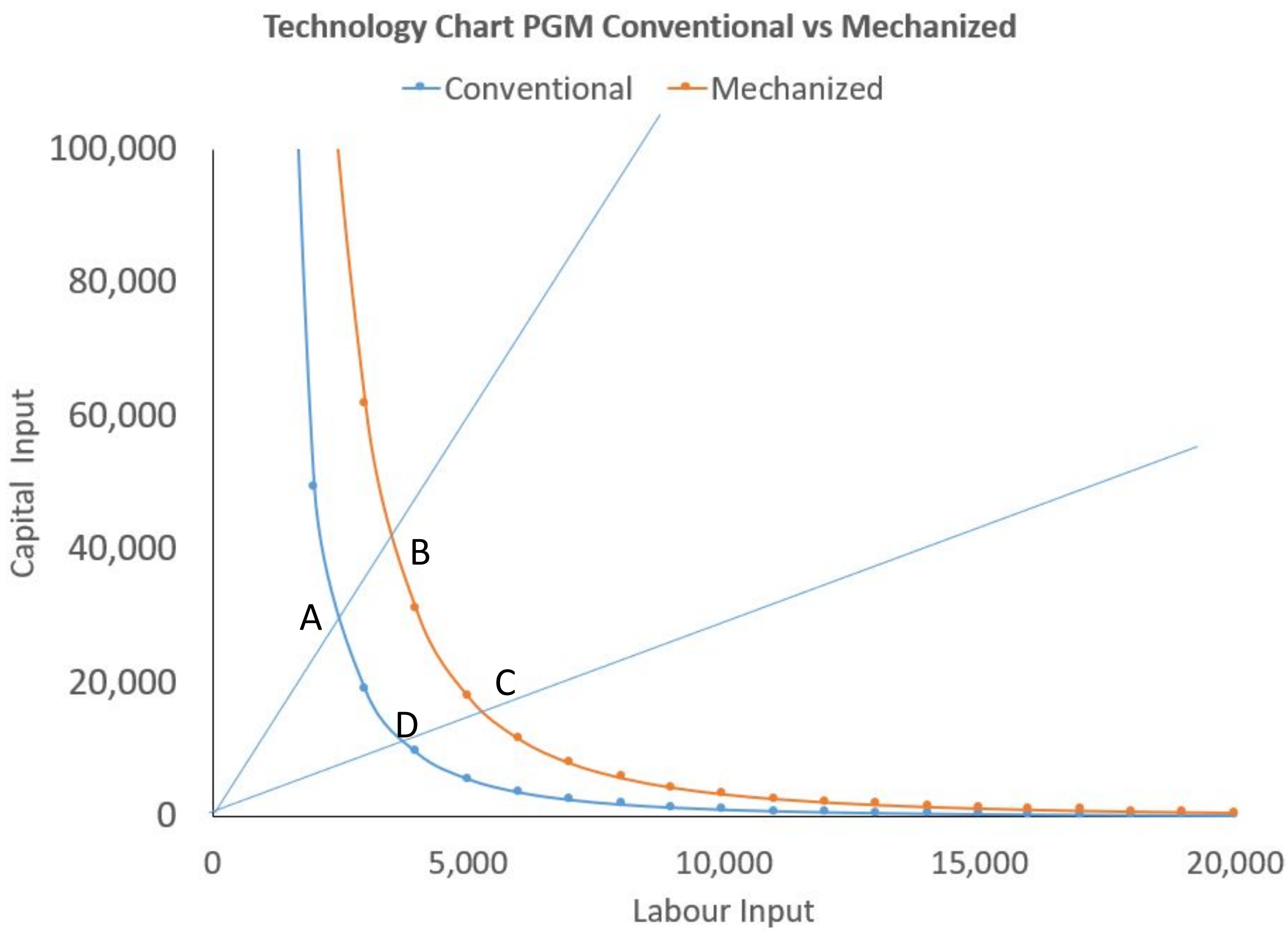
- Model was able to produce similar results as historical behaviour

Parameter	Unit	Conventional mining	Mechanized mining
Historical ore output (Q_h)	Tons/year	5,470	4,240
Stella Model Ore output (Q_m)	Tons/year	4,650	4,630
Quality Factor (A)	dimensionless	1,520 k	2,710 k
Historical productivity data	Kg of ore /employee /capital input	5.5	49.6
Capital Input Factor (K)	USD million	77.5	52.6
Capital Elasticity factor (α)	dimensionless	0.301	0.291
Labour Input Factor (L)	No of employee	15,000	7,100
Labour elasticity factor (β)	dimensionless	0.709	0.699

Summary findings – Technology QQ Charts

- Represents how output behaves in relation to the two technologies

- Shows biased technologies, where the ISO quants shifts due to a different technology



Discussion

The comparative analysis from the model highlights key outputs from a conventional mining system versus a mechanized mining system:

- **Output factor (Q):** The two systems analysed had similar and comparable production outputs which makes the results more meaningful as comparing like to like.
- **Total productivity factor (A):** The total productivity factor was higher for mechanised system compared to conventional mining systems. This may indicate that more ore is produced per each capital and labour input in the operations under a mechanized system. This agrees well with historical data which shows that 5.5 tons of ore were produced per each employee and capital input for conventional systems versus 49.6 tons per each employee and capital input. **Capital Inputs (K):** The capital inputs for the two systems were comparable.
- **Labour Inputs (L):** Conventional mining systems uses more labour to accomplish same output versus a mechanised system which uses less labour. 15,000 employees per each financial year whilst the mechanised system employed half of that for similar output.
- **Elasticity factors (α, β):** These were found to be 0.3 and 0.7 for both systems.

These findings suggest that **mechanised technologies can produce more output in comparison to conventional systems at the same capital input and less labour inputs.**

Systems dynamic modelling was therefore able to establish the impact factors of various technologies in a mining system that influences the mine output.

Conclusion

This study demonstrated the use of systems dynamic modelling using Stella software to determine the productivity factors of two technologies for platinum mining operations. From this study it is possible to conclude that:

1. **Systems dynamics** can be effectively used as a tool to compare the productivity of various technologies that can be used in underground platinum mining operations.
2. Having determined the **Total Productivity Factor (A)** for the system, the software can be used to determine the qualitative factors which influence the productivity of each technology system.
3. **Total Productivity factor for mechanised technologies is** higher than conventional technologies.

These results will be important in final modelling of a framework that can be used to select technology in a mining system.

Recommended Model Usage

This model can be used for

1. **Developing a Technology Decision Framework for a mining system** .
2. **Analyse long-term business returns based on various technologies**
3. **Optimise technology mix and technology change decisions**

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Biography

BIOGRAPHY

Christopher Mukonoweshuro. Currently a PhD candidate at the University of Witwatersrand, he holds an MSc engineering also from University of Witwatersrand and a BSc in mechanical engineering from the University of Zimbabwe. He is a member of the Southern African Institute of Mining and Metallurgy (SAIMM) and of the South African Institute of Mechanical Engineers (SAIMechE)

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