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Toward dynamic evaluations of materials criticality: A systems framework applied to platinum

Ye Yuan[a,*], Mohan Yellishetty[a], Gavin M. Mudd[b], Mario A. Muñoz[c], Stephen A. Northey[a], Tim T. Werner[d]

[a] Department of Civil Engineering, Monash University, Australia
[b] Department of Environmental Engineering, RMIT University, Australia
[c] School of Computer and Information Systems, The University of Melbourne, Australia
[d] School of Geography, The University of Melbourne, Australia

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ABSTRACT

A criticality assessment framework is introduced to quantitatively evaluate mineral supply-risk drivers, end-user vulnerabilities, market-dynamic indicators, and their interconnections in a time-dependent manner. Using this framework, we analyzed the criticality of platinum from 1975 to 2015, considering major regional end users (Europe, North America, Japan, and China) and producers (South Africa and Russia). Our analysis demonstrates that: (1) The global supply risk of platinum is strongly influenced by South Africa's socio-political status and its dominance over global supply and reserves; (2) Production from South Africa is directly affected by the level of social progress in the region, while price is indirectly affected; (3) Platinum prices are more closely associated with production from South Africa than those from North America and Russia; (4) These prices are more connected with consumption in North America than in other regions; (5) Europe is more vulnerable to supply restrictions than North America, Japan, and China in the context of economic importance, consumption and import reliance. Our methodology shows that a detailed, dynamic understanding of constraints, drivers and trends in material supply risks and vulnerabilities can be achieved, although this requires annual reporting of data that can be challenging to compile. As such, there remain challenges in replicating the assessments demonstrated here for other potentially critical metals.

1. Introduction

The 'criticality' of a metal is often defined by the risk of a supply restriction and the vulnerability of end users to such a restriction. Here, Platinum (Pt) is of broad concern as it is crucial to many important applications and is typically difficult to substitute (Mudd et al., 2018; Graedel et al., 2015b). Pt is also one of the rarest elements in Earth's upper crust and has an estimated abundance of approximately 0.005 ppm (Rudnick and Gao, 2003). In addition, the global supply of Pt is highly concentrated in regions which have experienced socio-political upheavals in previous decades (JM, 1975-2019JM, -, 2019JM, 1975-2019, Mudd et al., 2018, USGS, 1975-2019bUSGS, -, 2019bUSGS, 1975-2019b).

Several studies have assessed the criticality of Pt (Bauer and Li, 2010; BGS, 2012, 2015, DOE, 2010; EU, 2010, 2014, Graedel et al., 2015a; NRC, 2008), all of which have used *static-indicator-based* methodologies. As such, they have evaluated supply risks and vulnerabilities for a specified time instant, and hence are unable to account for *time dependencies*. Knoeri et al. proposed to address this issue by applying a conceptual assessment framework in which the agent-based modeling (ABM, the simulation of decision-makers' interactions) is integrated with a material flow analysis (MFA) to allow the dynamic evaluation of different types of demand-supply interactions. The differences between these interactions, in turn, help to differentiate the criticalities of different minerals (Knoeri et al., 2013). To date, no follow-up studies have been published to further develop methods for dynamic assessments of Pt criticality. Alonso et al. assessed the Pt supply risk and availability for future automotive technologies (Alonso et al., 2012). This study focuses on (1) three types of metrics including geophysical constraints (e.g., the static depletion index), institutional efficiency (e.g., the supply concentration), and dynamic factors (e.g., the demand-price elasticity), and (2) the evolutionary demand and supply for Pt in future automotive technologies. A drawback of this study is that it avoids the quantitative assessment of the statistical relationships between (1) the

* Corresponding author at: 38 College Walk, Monash University, Clayton, VIC, 3800, Australia.
E-mail address: ye.yuan@monash.edu (Y. Yuan).

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metrics used and (2) Pt demand, supply, or price. Some of these relationships are important for criticality assessment: for example, the relationship between the Pt depletion index and Pt price could inform how the geological availability of Pt affects its global market dynamics. Sverdrup et al. developed a systems-dynamic model to assess the long-term primary extraction, market supply, and reserve of Pt worldwide that considers variables such as fluctuations in the mining rate, changes in ore grade, demand, supply, and price (Sverdrup and Ragnarsdottir, 2016). This model does not explicitly evaluate the impact of exogenous variables (such as the social and political stabilities in major Pt-producing counties like South Africa) on Pt market dynamics. It has been shown that these impacts on the global Pt market are substantial (Day, 2014, Mudd et al., 2018).

In this paper, we introduce a dynamic assessment framework ↓ the *criticality system*, which is best described as an “observatory” that captures a bird’s-eye view of (1) changes in mineral supply-risk drivers, end-user vulnerability aspects, and variables reflecting mineral market dynamics, and (2) their interconnections. We demonstrate the potential of this framework by analyzing Pt criticality in the context of four major Pt-consuming countries/regions (the European Region, the North America Region, Japan, and China), and three major Pt-supplying countries/regions (South Africa, the North America Region [excluding Mexico], and Russia).

2. Methodology and data

2.1. General framework: criticality systems

The criticality system methodology, its underlying reasoning, and mathematical structure are presented in a previous study (Yuan et al., 2019). Here we only summaries it.

2.1.1. Overview

The criticality system has two layers: the *kernel* and the *outer layer*; both are schematically illustrated in Fig. 1. In the kernel, three types of *agents* ↓ mineral suppliers, consumers, and policymakers ↓ interact with each other. These interactions, such as bargaining between buyers and sellers are usually unobservable, due to such details being kept as privileged information. We, therefore, focus on the outer layer, which encompasses (1) metrics (the *constraints* and the *market variables*), and (2) interconnections (the *constraint-variable correlations* and the *mutual-variable correlations*).

The constraints are metrics selected to reflect different supply-risk drivers and end-user vulnerability aspects, such as the depletion time (supply risk) and the economic importance (vulnerability). In our framework, these constraints should be seen as the constraining factors affecting the agents’ decision making and interactions. These metrics are all time-series in nature, which means that evolutions of these metrics could affect the agents’ decision making over time. These constraints are adapted from the static indicators used by Graedel et al. in their *criticality space* to the supply risk and the vulnerability (Graedel et al., 2012). We expanded those indicators from a time instant into a time-series (Yuan et al., 2019). The market variables are also subject to change over time, as they reflect the changes in the consumption, production, price, and stock movement over time, all of which are affected in turn by the aforementioned agents’ interactions. These variables were selected according to the industrial market structure analysis (Ross, 1990; Scherer, 1996).

The constraint-variable correlations examine the statistical relationships among constraints and market variables. They reflect how the market performance changes in response to changes in supply risk and vulnerability. The mutual-variable correlations examine the statistical relationship among the market variables, reflecting how certain aspects of market dynamics change according to the changes of other aspects. Of note is that these correlation analyses are not limited to the *within-period* model, they also include the *inter-period* model or the *first-order difference* model.

In general, we propose that (1) there is a *complex system* surrounding a mineral that lies in both the anthroposphere and the lithosphere, and (2) the criticality system reflects a sequence of events in such a complex system. Namely, changes in the constraints lead to changes in the agents' interactions, which further affect the market variables. Then, via feedback loops, the disturbed market variables influence the entire system with latency. For instance, the decrease of a mineral’s depletion time (a change in the lithosphere) shifts the bargaining power from the buyers to the sellers (a change in the anthroposphere), which will lead to a rise of the price (further changes in the anthroposphere). The price rise, in turn, may result in increased mineral exploration and the increase of existing production. This then affects other variables in the complex system, including the future depletion time of the mineral

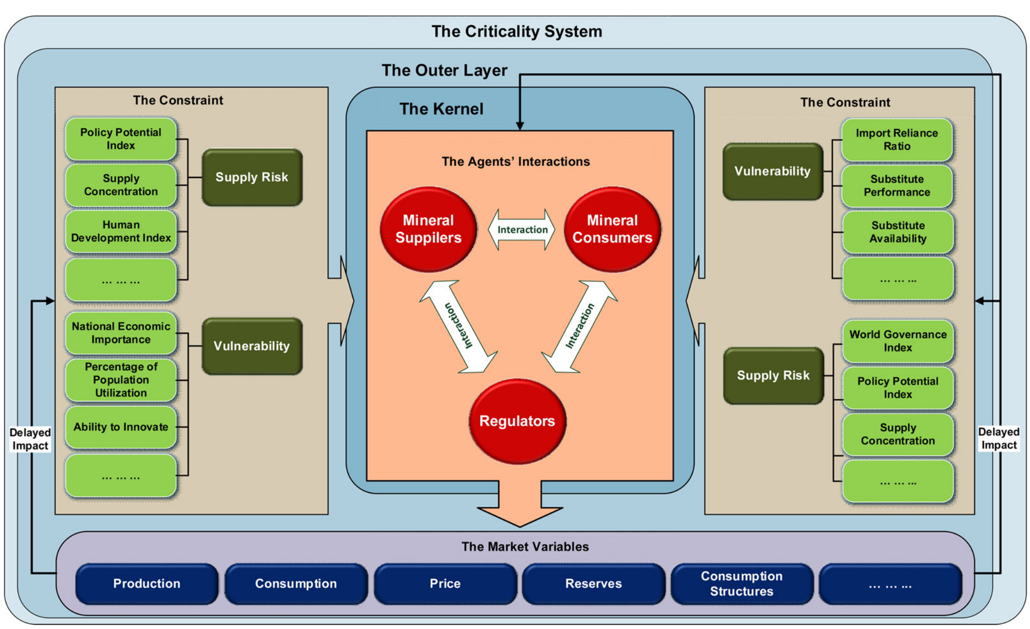

Fig. 1. Our proposed criticality system, including (1) the outer layer containing the constraints and market variables, (2) the kernel representing agent interactions, and (3) the feedback loops.

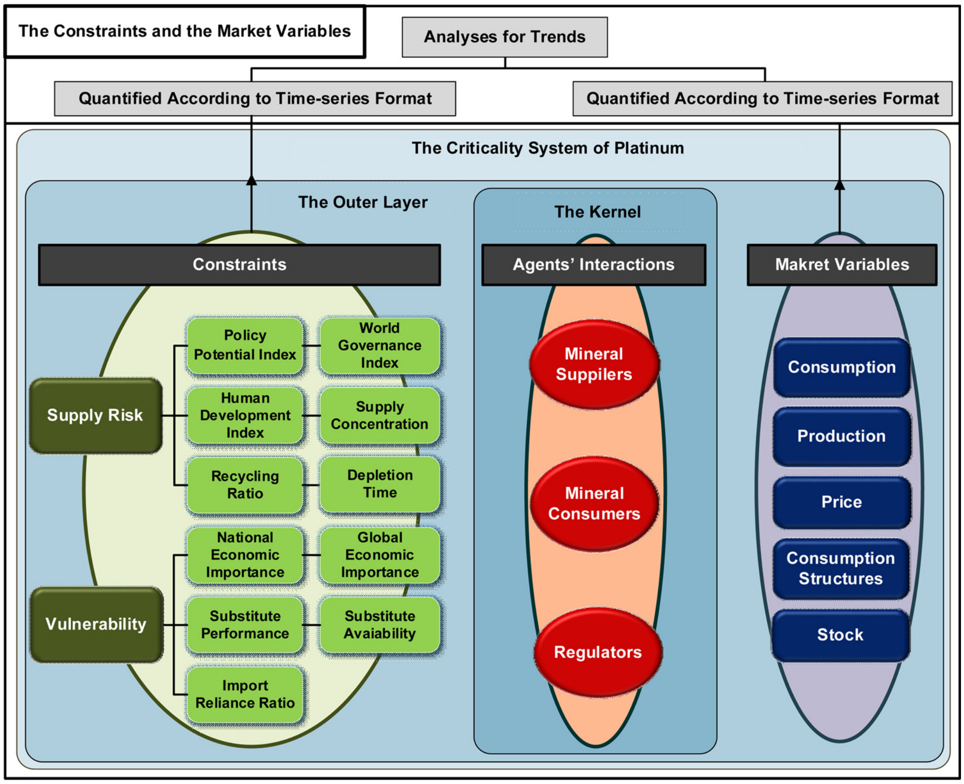

Fig. 2. Illustrates (1) the outer layer and the kernel of the criticality system of Pt, and (2) how the constraints and the market variables of the criticality system are analyzed for trends using statistical learning.

(further changes in the lithosphere and anthroposphere with latency).

2.1.2. Different dimensions of the criticality assessment

Using the criticality-system framework as a platform, one can analyze a mineral's criticality from two dimensions: the *mineral-focused* dimension or the *peer-focused* dimension. The former evaluates different mineral criticalities to a single end user (as per previous work, Yuan et al., 2019). This paper focuses on the latter, which analyzes the supply risk, the vulnerability, the market dynamics, and their interconnections from the perspectives of different end users.

2.2. The criticality system of platinum

The structure of the Pt criticality system follows the general methodological framework as per Section 2.1. Further, the details are presented in Sections 1–9 of Supporting Information. Results and analyses of the Pt criticality system are discussed in Section 3.

2.2.1. System structure

Figs. 2 and 3 illustrate the Pt criticality system. There are 11 constraints in the system: six reflecting different drivers of Pt global supply risk, and five reflecting different vulnerability aspects of the European Region (the ER), the North America Region (the NAR), Japan, and China to a Pt supply restriction. In Supplementary Tables 1 and 2, we discuss these 11 constraints and address how they influence various drivers of supply risk or vulnerability. These tables also consider how constraints are quantified. Notably, not all constraints in the general framework of the criticality systems are used in this study due to data availability. Additionally, longitudinal data for some constraints are difficult to obtain. Where possible, we discuss these from a point-in-time perspective, with a view to calibrating a balance between analytical rigor and data availability (see Graedel et al., 2012).

Figs. 2 and 3 also show the market variables and the correlations of the Pt criticality system. Notably, the correlations are non-exhaustive compared to that of the general framework of the criticality systems. In an attempt to avoid spurious correlations, we only selected a correlation for analysis if it had a reasonable prospect to reflect a direct cause-and-effect relationship based on existing studies (Alonso et al., 2012; Graedel et al., 2012, Mudd et al., 2018, Nassar, 2015; Ross, 1990; Scherer, 1996; Sverdrup and Ragnarsdottir, 2016).

2.2.2. Data sources

We compiled a penal-data matrix containing time-series datasets concerning Pt supply risk, vulnerability, and market variables. The datasets were acquired from both public and private sources, including the USGS Minerals Yearbook (USGS, 1975–2019bUSGS, -, 2019bUSGS, 1975–2019b), the USGS Mineral Commodity Summaries (USGS, 1975-2019aUSGS, -, 2019aUSGS, 1975-2019a), the BGS Global Mineral Production Data (Brown et al., 2012-2016Brown ., - et al., 2016Brown et al., 2012-2016), Johnson Mathey Platinum Market Reports (JM, 1975-2019JM, -, 2019JM, 1975-2019), the annual reports of Pt producers (AngloAmereican, 2012-2015AngloAmereican, -, 2015AngloAmereican, 2012-2015; Aquarius, 2012-2015Aquarius, -, 2015Aquarius, 2012-2015; Implants, 2012-2015Implants, -, 2015Implants, 2012-2015; Lonmin, 2012-2015Lonmin, -, 2015Lonmin, 2012-2015), and peer-reviewed publications (Alonso et al., 2012; Graedel et al., 2015b; Gunn, 2014; Mudd, 2012a, b; Nassar, 2015; Sverdrup and Ragnarsdottir, 2016).

We note that some clarifications are necessary for interpreting our data. Our use of the term "Pt production" is intended to reflect primary supply from mining activities. The secondary supply of Pt from recycling and stock are analyzed separately. All price-related metrics are inflation-adjusted according to US inflation (the CPI of the US in the year 2015). Most metrics and datasets related to the USA and Canada-based Pt production are aggregated. Thus, for production-related analyses, the USA and Canada are considered together. Furthermore, Mexico does not produce Pt at any significant level and is therefore excluded in these analyses. As a result, we refer to the corresponding

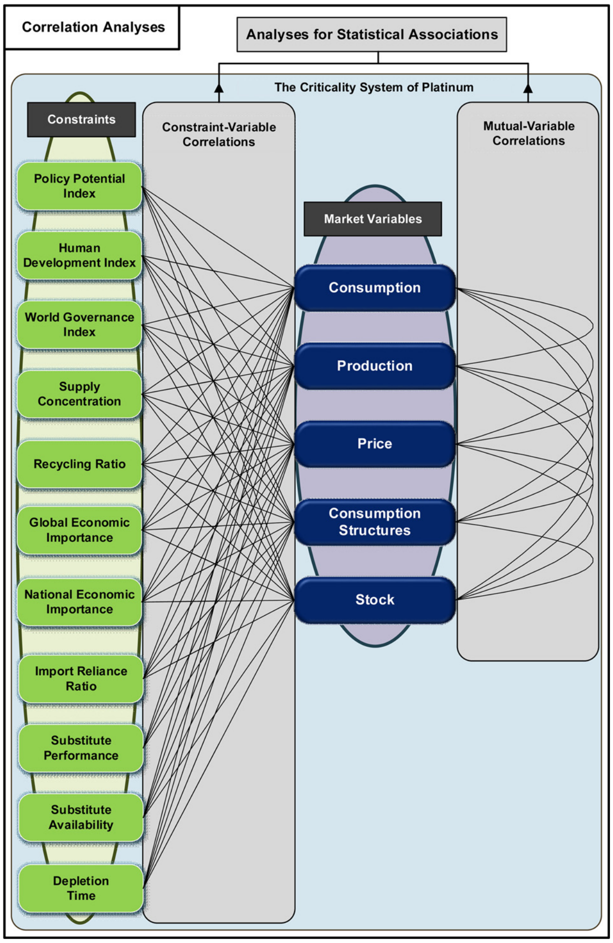

Fig. 3. Illustrates how the constraints-variable correlations and the mutual-variable correlations of the criticality system are analyzed for statistical associations using statistical learning.

geographical region as the NAR (excluding Mexico). For all consumption-related analyses, the US, Canada, and Mexico are all included in the NAR. Before 1993, the datasets concerning the ER include both Western Europe and Eastern Europe; for 1993 and the years after, the datasets still represent the information from the same region as before for the sake of consistency. Before 1991, datasets concerning Russia correspond to the former Soviet Union.

2.2.3. Methods of statistical analysis

The statistical analyses of the Pt criticality system's constraints and market variables can be categorized to two types: (1) the trend analyses, evaluating their changes over time looking for deterministic trends; (2) the correlation analyses, assessing their statistical associations analyzing possible causal directions. For statistical robustness, these two types of analyses need to be structured in an orderly manner. As such, we propose a statistical-analysis framework for the Pt criticality system, which can be summarized as follows:

2.2.3.1. Deterministic-trend analyses.

(a) Conduct the trend analysis of a constraint or a market variable using linear methods such as ordinary least squares (OLS) regression, and diagnose the regression analysis using the residuals-fitted analysis, normal Q-Q analysis, etc. The OLS model, in this case, can be described by Eq. (1) below,

$$y_t = \alpha_0 + \alpha_1 t + \varepsilon_t \tag{1}$$

where ε_t is a random error term with mean zero and unknown variance, α_0 and α_1 are the constant and the coefficient.

(a) If diagnosis shows that the OLS regression is inappropriate, non-linear models such as the natural exponential growth model described by Eq. (2) will be used to fit the trend.

$$y_t = c_0 + e^{(\alpha_0+\alpha_1 t)} + \varepsilon_t \tag{2}$$

where ε_t is a random error term with mean zero and unknown variance, c_0 is the constant term, and α_0 and α_1 are the coefficients.

(a) If the non-linear models are still inappropriate, the *smoothing-spline method* is used, which minimizes the following cost function:

$$\sum_{t=0}^{t=n} (y_t - g(t))^2 + \lambda \int g''(t)^2 dt \tag{3}$$

where n is the length of this time-series dataset starting from zero, function y is assumed to be the unknown function that generates the time series, λ is a non-negative tuning parameter and is tuned using both *validation-set approach* and *cross-validation*, and function g is the smoothing spline that minimizes Eq. (2) and thus best estimates function y.

2.2.3.2. De-trending

(a) De-trend all constraints and market variables using their deterministic trends.
(b) Test all de-trended constraints and market variables for stationarity.

2.2.3.3. Correlation analyses of de-trended stationary time-series datasets.

(a) Apply *autoregressive-distributed lag modeling* (ARDL) to the de-trended stationary series, considering only lag 1 or lags 1 and 2 (via Akaike Information Criterion, or simply AIC, we find that the significant lags of almost all the de-trended stationary series are of lag-1 or lag-2 significant).

$$y_t = \beta_0 + \beta_1 y_{t-1} + \beta_2 y_{t-2} + \alpha_0 x_t + \alpha_1 x_{t-1} + \alpha_2 x_{t-2} + \varepsilon_t \tag{4}$$

where ε_t is a random error term with mean zero, y_t is the response variable at period t, y_{t-1} and y_{t-2} are the lags 1 and 2 of the response variable, x_t is the input variable at period t, x_{t-1} and x_{t-2} are the lags 1 and 2 of the input variable, and β_0, β_1, β_2, α_0, α_1, and α_2 are the constant and the coefficients (Tables 1 and 2).

3. Results & analysis: the Pt criticality system

3.1. Constraints: six aspects of supply risk

3.1.1. PPI, HDI, and WGIPV

South Africa, Russia, and the NAR (excluding Mexico) supplied more than 90% of global cumulative Pt production from 1975 to 2015 (JM, 1975-2019JM, -, 2019JM, 1975-2019; USGS, 1975-2019aUSGS, -, 2019aUSGS, 1975-2019a). Thus, in order to assess the components of global Pt supply risk reflecting (1) governmental and non-governmental barriers to mining activities, (2) conflicts of the social values, and (3) societal-political instabilities, we focus on the PPIs, HDIs, and WGIPVs of these countries/regions. Fig. 4 highlights changes in these indices over time.

Table S4 shows their average values over time, their trend analyses, and their values in 2015. The NAR (excluding Mexico) has the highest average values of the PPI (2001 to 2015), the HDI (1990 to 2015), and the WGIPV (1996 to 2015) compared to the rest, indicating the highest level of the administrative competency of the government, social progress, and political stability; South Africa and Russia, on the other hand, have much lower average values of these indices. We argue that South Africa has a greater impact on global Pt supply risk than do Russia and

Table 1
A summary of the constraints of the platinum's criticality system: six aspects of the supply risk.

Nature of the Constraints	Quantification and Trend Analyses
Policy Potential Index (PPI) Developed by Fraser Institute, PPI assesses the impact of governmental and non-governmental barriers on mining and exploration activities in a country; a low value of this index suggests the higher barriers (McMahon, 2011). We selected this index as a driver of Pt's supply risk according to Graedel et al. and their criticality-assessment framework (Graedel et al., 2012).	• Estimate the deterministic trends of the PPIs of the top-three platinum-producing counties/regions overtime: South Africa, Russia, and the NAR (excluding Mexico). • Calculate the Weighted PPI (WPPI) for platinum based on these counties/regions over time. WPPI for platinum of a specific year is calculated by weight-averaging the PPI scores of these major platinum-producing counties/regions by their annual Pt production in that year. The equation for this calculation — Equation S1 — is presented in Supporting Information. Estimate the deterministic trend of WPPI.
Human Development Index (HDI) Developed by the United Nation Development Program, the HDI assesses the level of social progress and human development of a country considering three aspects: the citizen's health condition, their education levels, and their living standards. According to Graedel et al., a society with a high level of social progress and human development tends to value life quality and environmental protection above the intrusive development of the mining industry (Graedel et al., 2012).	• Estimate the deterministic trends of the HDIs of South Africa, Russia, and the NAR (excluding Mexico). • Calculate the Weighted HDI (WHDI) for platinum based on these counties/regions over time. Pt's WHDI is calculated similarly to that of WPPI. The equation for this calculation — Equation S2 — is presented in Supporting Information. Estimate the deterministic trend of WHDI.
World Governance Index - Political Stability & Absence of Violence -Ranking (WGIPV) Developed by the World Bank, the WGAPV assesses the political and social stabilities of a nation compared to others; a low value of this index suggests a high level of political uncertainties, which poses a higher risk to mining activities. This constraint is selected for Pt's criticality system according to Graedel et al. and Mudd et al. (Graedel et al., 2012, Mudd et al., 2018).	• Estimate the deterministic trends of the WGIPVs of South Africa, Russia, and the NAR (excluding Mexico). • Calculate the Weighted WGIPVs (WWGIPVs) for platinum based on these counties/regions over time. Pt's WWGIPVs is calculated similarly to those of WPPI and WHDI. The equation for this calculation — Equation S3 — is presented in Supporting Information. Estimate the trend of WWGIPV.
Global Supply Concentration (GSC) Given all else being equal, a high level of the supply concentration leads to less competition and more bargaining power to the seller (Cournot, 1838; Graedel et al., 2012; Von Stackelberg, 1952), thus it is a factor of supply risk. We use the CR3 (Concentration-ratio 3) index to reflect the GSC.	• Calculate Pt's CR3 indices at a corporate level over time (referred to as the corporate-level CR3 index). The equation for this calculation — Equation S4 — is presented in Supporting Information. Estimate the deterministic trend. • Calculate Pt's CR3 indices at a national/regional level over time (referred to as the national-level CR3 index) according to Equation S4 in Supporting Information. Estimate the trend.
Depletion Time (DT) DT estimates the time (in years) required to deplete the current known Pt resources underground using variables such as the current and projected future demand.	• Pt's static depletion index calculated by Alonso et al. is used (Alonso et al., 2012).

the NAR (excluding Mexico). This is primarily as South Africa's contribution to global Pt production is several times more than that of Russia and the NAR (excluding Mexico) combined (JM, 1975-2019JM, -, 2019JM, 1975-2019; USGS, 1975-2019aUSGS, -, 2019aUSGS, 1975-2019a). South Africa alone holds ~88% of known platinum group metal (PGM) reserves (Alonso et al., 2012), and further has low and stagnated PPI, HDI, and WGIPV. A low PPI, HDI, and WGIPV of a mining region have been shown to increase the supply risk of minerals

Table 2
A summary of the constraints of the platinum's criticality system: five aspects of the vulnerability.

Nature of the Constraints	Quantification and Trend Analyses
Global Recycling as the Percentage of Consumption (RPC) A mineral's RPC reflects the ratio of the amount recycled globally to the global consumption of the mineral at a given year, this provides insights into the recyclability as an aspect of the supply risk (Graedel et al., 2012)(Graedel, 2015).	• Calculate Pt's RPC over time, and estimate the trend.
Global Economic Importance (GEI) The GEI reflects how economically importance a mineral is. We analyze Pt's GEI in terms of different Pt's end-use sectors.	• Calculate Pt's GEI and the global economic importance in the following end-use sectors: catalytic, jewelry, chemical, glass, petroleum, and electrical (referred to as end-use sectors). These calculations are based on the yearly consumption statistics of these end-use sectors and the inflation-adjusted price according to Equation S5 in Supporting Information. Estimate the trend of Pt's GEI.
National Economic Importance (NEI) While the GEI reflects a mineral's economic importance at a global scale, the NEI repeats it at a national or regional level. We analyze Pt's NEI to the NAR, the ER, Japan, and China; we also identify the economically important Pt's end-use sectors in these countries/regions.	• Calculate the NEIs of platinum to the ER, the NAR, Japan, and China. These NEIs are calculated according to Equation S6 in Supporting Information. Trends are estimated. • Identify the economically important Pt's end-use sectors in these countries/regions (top one of all end-use sectors in terms of economic importance). Trends are estimated.
Import Reliance Ratio (IRR The IRR reflects the reliance of a country/region to import supply restriction. We focus on the analysis of IRRs of major platinum-consuming countries/regions.	• Calculate Pt's IRRs of the ER, the NAR, Japan, and China according to Equation S7 in Supporting Information. Trends are estimated.
Substitute Performance (SP) The SP reflects the substitute performances of a mineral. We evaluate Pt's SPs in different Pt's end-use sectors according to their Substitute Performance Scores (PSPSs). An end-use sector that does not have a high-performance substitute is more vulnerable to Pt's supply restriction. We also evaluate the impacts on the ER, the NAR, Japan, and China should Pt's supply be restricted using Platinum Substitute Performance Impact Index (PSPII)	• Evaluate Pt's Substitute Performance Scores (PSPSs) of eight Pt's end-use sectors according to Tables S1 in Supporting Information. The evaluation method is adopted from Graedel et al. (Graedel et al., 2015b). • Calculate Platinum Substitute Performance Impact Indices (PSPIIs) of the ER, the NAR, Japan, and China over time. The PSPII is calculated according to Table S2 and Equation S8 in Supporting Information. Trends are estimated.
Substitute Availability (SA) The SP reflects the substitute availability of a mineral. We evaluate Pt's SAs in eight Pt end-use sectors. An end-use sector that does not have a high-performance substitute is more vulnerable to Pt's supply restriction. We also evaluate the impacts on the ER, the NAR, Japan, and China should Pt's supply be restricted using Platinum Substitute Availability Impact Index (PSAS).	• Evaluate Pt's Substitute Availability Scores (PSASs) of eight Pt's end-use sectors according to Graedel et al. (Graedel et al., 2015b). • Calculate Platinum Substitute Availability Impact Indices (PSVIIs) of the ER, the NAR, Japan, and China over time. The PSVI is calculated according to Table S3 and Equation S9 in Supporting Information. Trends are estimated.

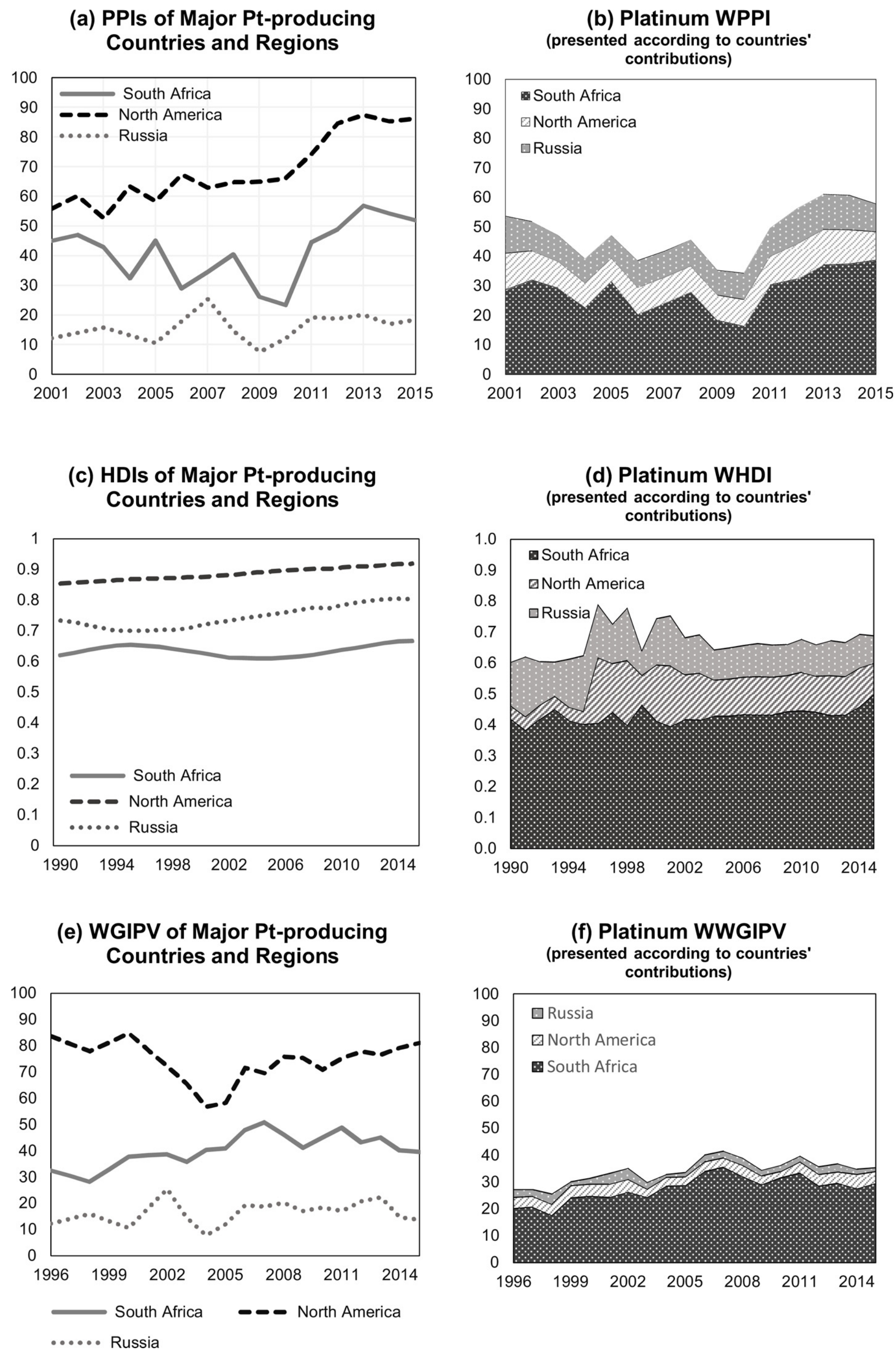

Fig. 4. (1) The PPIs (McMahon, 2011), HDIs (UN, 1990-2015), and WGIPVs (Kaufmann and, 1996–, 2015) of South Africa, Russia, and the NAR (excluding Mexico) (a, c, and e). (2) Pt's WPPI, WHDI, and WWGIPV calculated according to Equation S1, S2, and S3 in the Supporting Information, and presented in terms of contributions (b, d, and f).

produced from this region (Graedel et al., 2012, Mudd et al., 2018).

3.1.2. Global supply concentration (GSC)

The highly concentrated global supply of Pt is considered by many to be a prominent component of its supply risk (Alonso et al., 2012; Graedel et al., 2015a, Mudd et al., 2018). The average value of the Pt annual national-level CR3 index from 1975 to 2015 is 0.962 (Table S4). South Africa, Russia, and the NAR (excluding Mexico) each contributed 0.749, 0.165, and 0.048 to this value respectively, leaving South Africa as the only dominant figure. Of note is that Pt production from South Africa almost exclusively comes from a single mining region ↓ the Bushveld Igneous Complex ↓ that encompasses three layers of Pt-rich igneous rock including the Merensky reef, the UG-2 reef, and the Platreef (Mudd et al., 2018). Together with low societal-political stability ratings in South Africa (discussed in Section 3.1.1), such a concentrated supply pattern has been shown to be easily disturbed. In 2014, a five-month labor strike crippled the Pt production output from the Bushveld region for almost an entire year. In 2012, the Marikana riots, which led to 34 deaths, also had serious adverse effects on the region's Pt production (Harvey, 2016, Mudd et al., 2018).

As shown in Table S4, Part (a) of Fig. 5, and Figure S2 in Supporting Information, the national-level CR3 index decreased from 1975 to

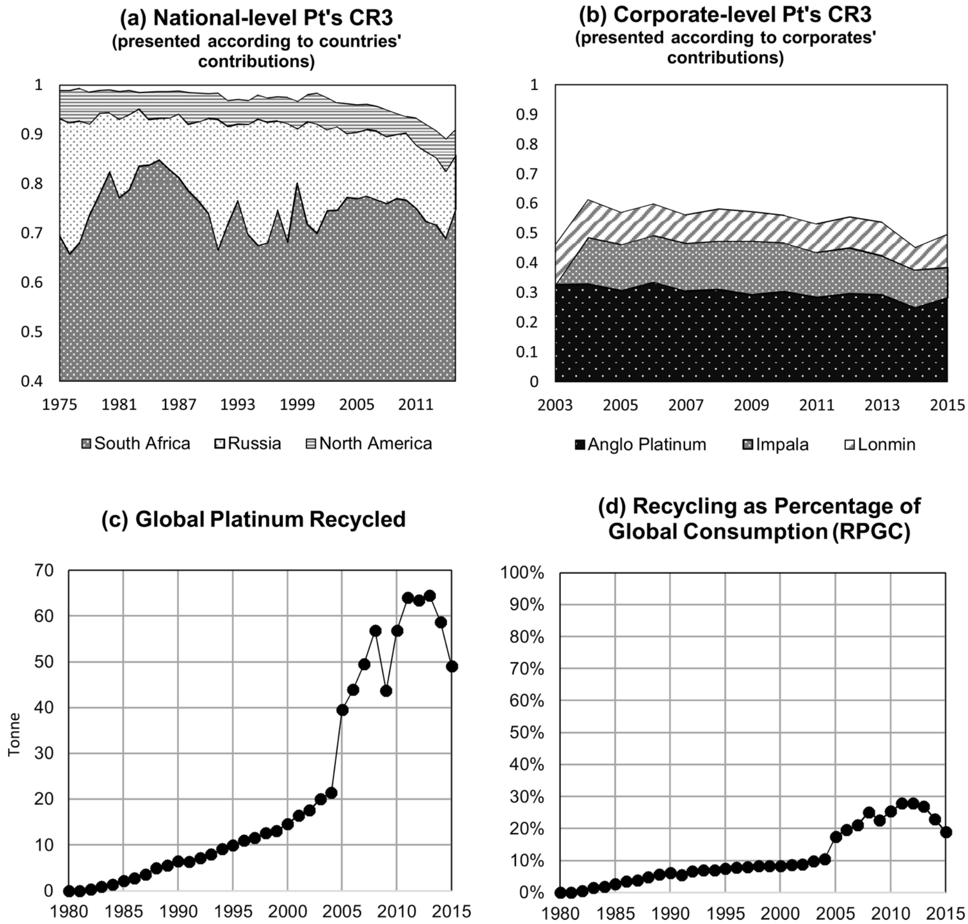

Fig. 5. (a) Pt national-level CR3 index; (b) Pt corporate-level CR3 index; (c) Pt global recycling tonnage; (d) Pt RPGC.

2015, and best fits a deterministic trend that follows

$$y_t = 1 - e^{(\alpha_0 + \alpha_1 t)} + \varepsilon_t \quad (5)$$

where α_0 and α_1 are the coefficients with values of $-1.51 \cdot 10^2$ and $7.286 \cdot 10^{-2}$. This indicates that the global supply concentration level was decreasing exponentially. A careful examination of global Pt production from 1975 to 2015 (Brown et al., 2012-2016Brown ., - et al., 2016Brown et al., 2012-2016; JM, 1975-2019JM, -, 2019JM, 1975-2019; USGS, 1975-2019aUSGS, -, 2019aUSGS, 1975-2019a; 1975-, 2019b) reveals that this trend is caused by the increase of production from newly emerging countries (e.g., Zimbabwe) rather than the reduction of production from the dominating incumbent (e.g., South Africa).

At a corporate level, five international conglomerates (Anglo Platinum, Lonmin, Norilsk Nickel, Implants, and Inco, control most of global Pt supply, suggesting that the global market can be described as an oligopoly (Alonso et al., 2012). According to Table S4, the average corporate-level CR3 index from 2003 to 2015 is 0.649 owing to predominant roles of Anglo Platinum (AngloAmereican, 2012-2015AngloAmereican, -, 2015AngloAmereican, 2012-2015), Implants (Implants, 2012-2015Implants, -, 2015Implants, 2012-2015), and Lonmin (Lonmin, 2012-2015Lonmin, -, 2015Lonmin, 2012-2015). Of note is that Anglo Platinum alone controlled 32.6 percent of worldwide cumulative production during this period (see Fig. 5(b)).

3.1.3. Depletion time (DT)

According to the static depletion index calculated by Alonso et al., documented global mineral resources in 2012 can meet global Pt consumption over the next hundred years, assuming that consumption stays constant over time. If the exponential growth trend observed for global Pt consumption from 1980 to 2010 is used for future projection, known Pt mineral resources as at 2012 would meet the projected consumption for the next 56 years (Alonso et al., 2012). On the other hand, the depletion index threshold that requires attention and effort for serious exploration is 30 years or below (Alonso et al., 2007a; Tilton, 2010). These suggest that geological availability does not contribute significantly to the global supply risk of Pt. Other studies appear to confirm this conclusion. For instance, according to Mudd et al., the known PGM mineral resources worldwide in 2015 contained ~105,682 t PGMs (4E-basis), which is relatively abundant compared to known mineral resources of other critical minerals such as rare earth elements (Mudd et al., 2018). However, the relative abundance of Pt mineral resources should not mask the fact that the resource concentration of Pt is low compared to other metals such as copper, zinc, or gold (Nassar, 2015). Common Pt ore grades are around 1 g/t, which is an important factor in high production costs, high prices, and high greenhouse gas emissions in the production of Pt (Alonso et al., 2012).

3.1.4. Recycling

As shown in Fig. 5(c), global Pt recycling rates increased substantially from 1980 to 2013. A sector-wise analysis shows that a majority of the recycled Pt were recovered from autocatalytic and jewelry scrap (JM, 1975-2019JM, -, 2019JM, 1975-2019). From a national/regional perspective, the US, EU, and Japan contributed the most significantly to the global Pt recycling growth trend shown in Fig. 5(c). As early as 1998, ~76% of end-of-life products containing Pt in the US were recovered for recycling (Alonso et al., 2012). As of 2006, many countries in the EU had targeted end-of-life vehicles for recycling, with a few countries including Austria and Germany starting to recycle almost 100% of their retired automobile fleets (JM, 1975-2019JM, -, 2019JM, 1975-2019).

Of note in Fig. 5(c) is the dramatic increase in Pt recycling from 2004 to 2008. This sudden burst of growth coincides well with the Pt price spike during the same period (see Fig. 10(a)) and the rapid increase of global Pt stockpiling (see Fig. 10(b)). While it is possible that a sudden change of Pt global recycling volumes could have caused the changes in Pt stockpiling intensity and the price, the reverse is more likely. The soaring price ignited the Pt recycling industry, as many previously unprofitable recycling businesses had just become economically viable.

Based on the annual recycling of Pt, we further calculated the recycling as a percentage of global consumption (RPGC). The growing trend of RPGC peaked at ~28% in 2012.

3.1.5. Primary Pt supply risk drivers

The combination of South Africa's socio-political status and dominance over global Pt supply (and reserves) appears to be the most significant supply risk factor. Historically, this combination has proven problematic, for example in the 1977 cobalt crisis with Zaire (Alonso et al., 2007b) and the 1997 palladium market crunch with Russia (Alonso et al., 2008). Of note is that Zaire only controlled ~48% of the world production of cobalt and Russia only contributed to ~42% of the global production of palladium; both much lower than South Africa's current ~75% share.

3.2. Constraints: five aspects of vulnerability

3.2.1. Global and National Economic Importance (GEI & NEIs)

Fig. 6 shows the growth of Pt GEI over time, with the trend analysis of Pt GEI using the smooth spline method provided in Fig. S2. Further analyses of the GEI and NEI are provided in Table S5. The GEI in 2015 was 9.611 billion USD, while the average annual GEI from 1975 to 2015 is 5.591 billion USD. This difference suggests that annual GEI was rapidly growing. In particular, the GEI from 2000 to 2008 experienced a surge, as shown in Fig. 6. The surge was largely driven by the strong growth of the global autocatalytic consumption and the subsequent price rise during this period (JM, 1975-2019JM, -, 2019JM, 1975-2019). The comparison of Fig. 6(a)–(b) illustrates the impact of autocatalytic growth. Indeed, the global autocatalytic sector is the largest when compared to the rest in terms of the economic value of Pt consumption since 1975. In 2015 alone, 101.6 t Pt (~3.8 billion USD) was consumed for manufacturing autocatalytic converters.

For the NEI analysis, we focused on NEI in the ER, the NAR, Japan, and China, who consumed over 85% of global Pt production over the last 30 years (JM, 1975-2019JM, -, 2019JM, 1975-2019). Fig. 6 (c) depicts the NEI from 1975 to 2015. Part (c) of Table S5 lists the average annual NEIs during this period and the annual NEIs in 2015. Sections 1.7.2 to 1.7.5 of the Supporting Information present the sector-level analyses of economic importance to the ER, the NAR, Japan, and China. In 2015, the NEI of Pt in China was the highest at ~ 2.71 billion USD. On the other hand, during the period from 1975 to 2015, cumulative NEI to the ER was the largest. Of note is the period between 2000 and 2008, during which the Pt NEI to all four countries/regions experienced an increase, but the NEIs of the ER and China increased the fastest, as shown in Fig. 6(c). The drivers behind this growth differ depending on specific countries/regions. The increase of the NEIs to the ER and the NAR was mainly due to the growth of their autocatalytic sectors, whereas the increase of NEI to China was driven by the growth of its jewelry sector (see Fig. S5). The autocatalytic sector is the most economically important Pt end-use sector in both the ER and the NAR. From 1957 to 2015, the net worth of Pt consumed in the ER autocatalytic sector accounts for 79.3% of the entire NEI to the region, while for the NAR, this is 51.7%. On the other hand, jewelry is the only dominant sector in China, which accounts for 82.2% of the overall Pt NEI to the region from 1996 to 2015.

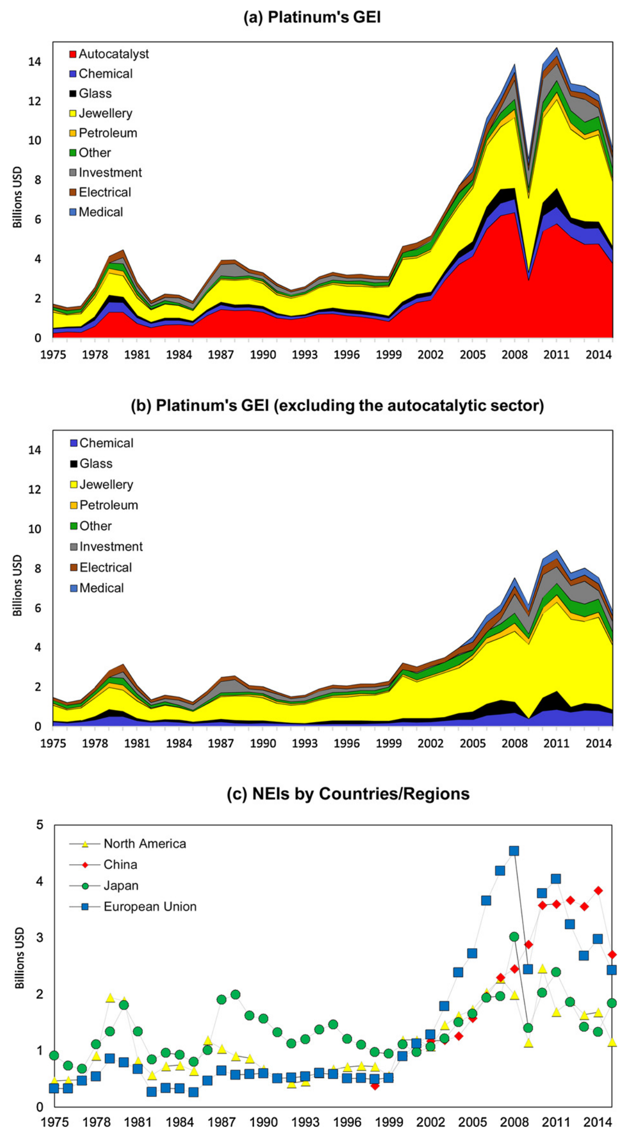

Fig. 6. (a) The GEI of Pt presented in terms of different end-use sectors; (b) the GEI of Pt excluding the autocatalytic sector; (c) the NEIs of Pt to the ER, the NAR, Japan, and China, from 1975 to 2015.

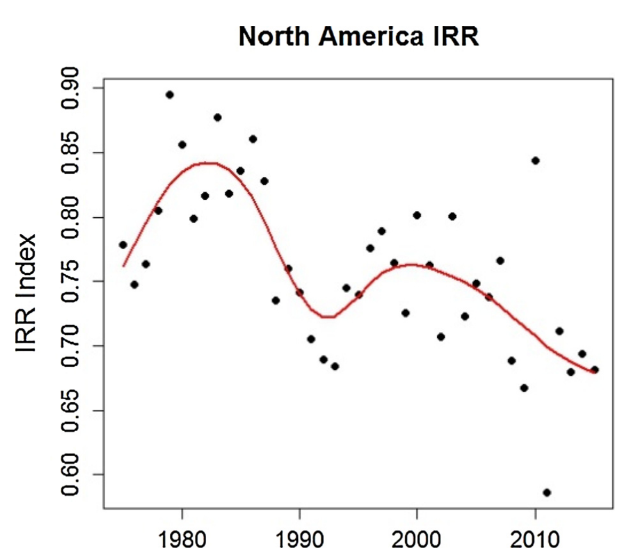

Fig. 7. Plot and the trend analysis of the NAR IRR for Pt.

3.2.2. Import Reliance Ratio (IRR)

The NAR is the only one among these four Pt-consuming counties/regions that do not entirely depend on overseas Pt supply. In 2015, its IRR for Pt was 0.682. From 1975–2015 (Fig. 7), the NAR IRR for Pt showed a general downward trend with a seasonal pattern, suggesting that Pt consumption was increasingly met by Pt production within the region.

3.2.3. Substitute performance

We evaluated the performance of Pt substitutes in eight end-use sectors using a Platinum Substitute Performance Score (PSPS) & Substitute Performance Impact Index (PSPII). The petroleum sector, the catalytic sector (especially the diesel-catalytic sub-sector), and the glass sector received the score of 0.875 for their PSPSs, suggesting that Pt substitutes ↓ molybdenum (Mo), palladium (Pd), and iridium (Ir) ↓ perform poorly in these sectors. On the other hand, Pt substitutes in the jewelry and investment sectors ↓ palladium and gold ↓ perform well (functionally speaking), leading to the PSPSs of 0.375 for both sectors. The evaluation procedure for the PSPSs is presented in Section 1.9 of Supporting Information and the results for all end-use sectors' PSPSs are discussed in Table S2.

The PSPII of a country/region measures the impact of a Pt supply restriction on the economy by considering the economic scales of different end-use sectors in the country/region and the PSPSs of these sectors. The calculation procedure for the PSPII is presented in Section 1.9.2 of Supporting Information. We calculated the PSPIIs of the global economy from 1975 to 2015. Fig. 8 (a) depicts the global PSPII in terms of different end-use sectors' contributions during this period. It shows a moderate growth trend from ~0.5 in 1975 to ~0.6 in 2015. The PSPIIs of the global catalytic sector and the global jewelry sector contributed the most to global PSPII growth. We also calculated the PSPIIs of the NAR, Japan, the ER, and China (see Fig. 8(b)). The NAR was the highest during the period from 1975 to 1999; its PSPII peaked in 1990 with a score of 0.89 and then continued to decline. From 1999 to 2015, the ER's PSPII surpassed that of the NAR and became the highest, suggesting the NAR has become the most susceptible to a Pt supply restriction.

3.2.4. Substitute availability

We calculated the availability of Pt substitutes in eight end-use sectors using Platinum Substitute Availability Scores (PSAS) & the Substitute Availability Impact Index (PSAII). The petroleum, glass, chemical, and investment sectors scored 0.64, 0.61, 0.63, and 0.61 for their PSASs respectively, suggesting a bigger impact than others in the event of a Pt restriction. Pt substitutes in these sectors are molybdenum (Mo), iridium (Ir), Cobalt (Co), and gold (Au), all of which face a high risk of supply disruption. The evaluation procedure for the PSASs is presented in Section 1.9.3 of Supporting Information, with the results of all end-use sectors' PSASs discussed in Table S3. Similar to PSPIIs, PSAIIs consider two factors: the economic scales of the different Pt-end-use sectors and the PSASs of these sectors. The calculation procedure for the PSAII is presented in Section 1.9.4 of Supporting Information. Fig. 8 depicts the global PSAII and the PSAIIs of the ER, the NAR, Japan, and China, from 1975 to 2015. The NAR's PSAII was higher than those of the rest during the entire period from 1987 to 1999.

3.2.5. Pt vulnerability in the European Region

The ER merits extra attention for its vulnerability, as from 1975 to 2015, the cumulative NEI to the ER is significantly higher than those of the NAR, Japan, and China, indicating a higher level of vulnerability to supply restriction. In 2015, ~80% of Pt NEI to the ER was due to its autocatalytic sector. In comparison, this value for Japan, the NAR, and China are 26%, 40%, and 5% respectively. As the autocatalytic converter is a highly necessary product and thus does not respond to supply

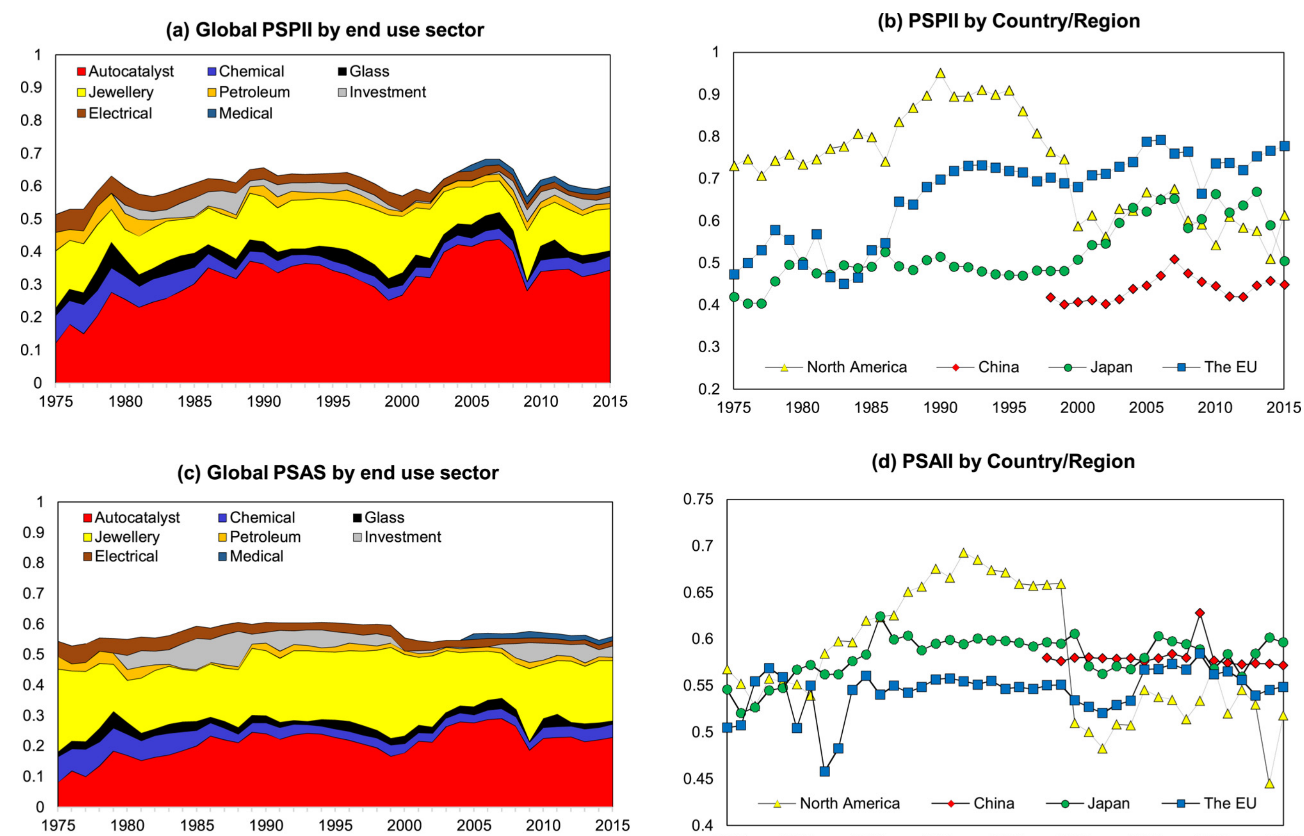

Fig. 8. (a) The global PSPII per end-use sector; (b) the PSPIIs of the ER, the NAR, Japan, and China; (c) the global PSAII; (d) the PSAIIs of the aforementioned countries/regions.

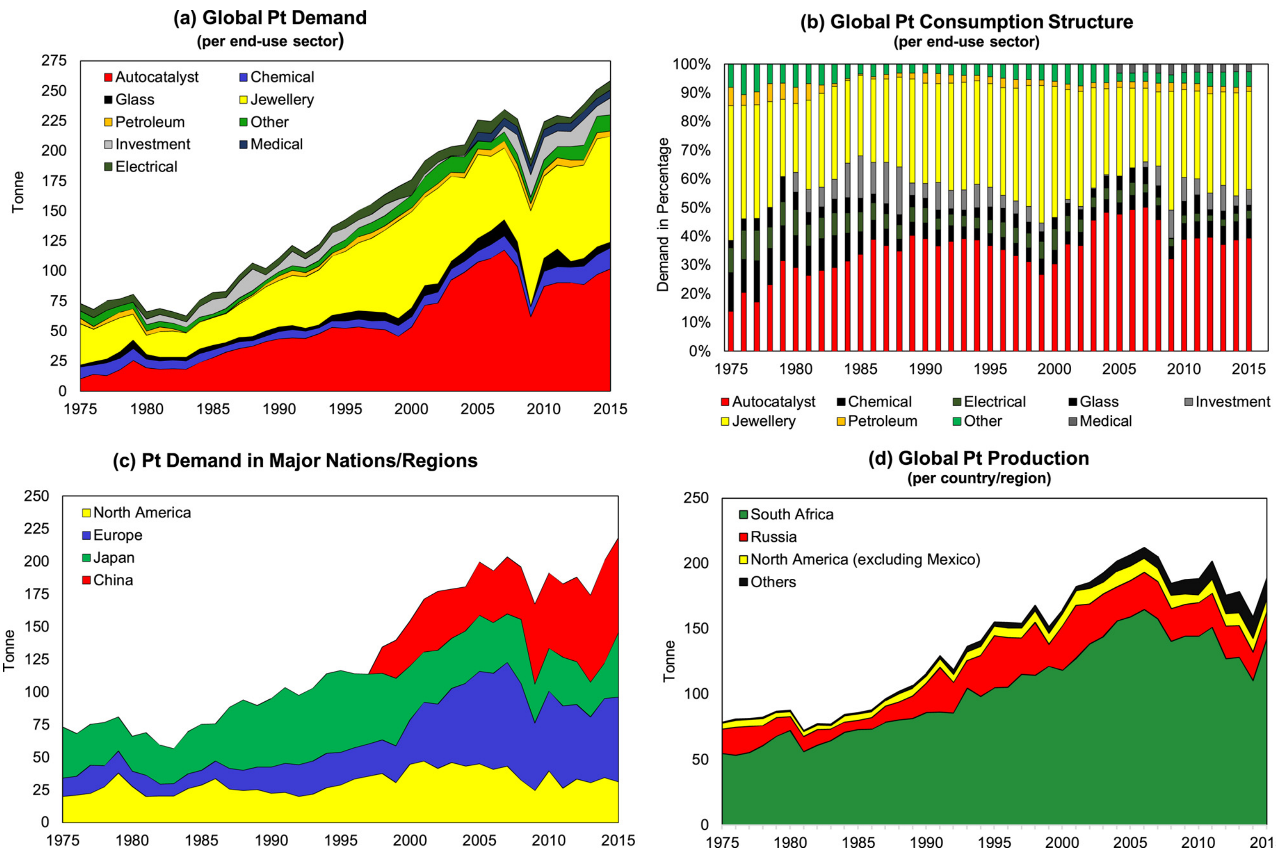

Fig. 9. (a) Pt consumption worldwide from 1975 to 2015 presented in terms of different end-use sectors, (b) Pt consumption structure, (c) Pt's consumptions of major consuming counties, and (d) Pt's production worldwide presented in terms of different countries and regions.

restrictions and price changes well compared to other Pt applications (e.g. jewelry), the ER's vulnerability is particularly notable. Additionally, the ER's demand is met entirely through imports, and the ER's PSPII in 2015 is the highest compared to others.

3.3. Market variables

3.3.1. Global Pt consumption and production

Global Pt consumption grew steadily from 73.14 t in 1975 to 258 t in 2015, with fluctuations induced by the global financial crisis (Fig. 9). Additional analyses of Pt consumption in different end-use sectors and in different countries and regions are provided in Table S6. Globally, the autocatalytic and jewelry sectors are the first and the second in terms of the sector-wise Pt consumption. From 1975 to 2015, autocatalytic converters and jewelry accounted for 38.25% and 35.06% of total consumption respectively. Arguably, the large consumption in the global autocatalytic sector is driven by the ever-growing automotive fleet in the world (practically in newly emerged economic giants such as China and India), and the tightened emission regulations in the ER, Japan, and the NAR, which require more Pt be used per vehicle (Alonso et al., 2012; Mudd, 2012b). On the other hand, strong Pt consumption in the global jewelry sector is due to China's growing appetite for Pt-made jewelry. China was the biggest Pt-consuming country from 1998 to 2015, as its annual consumption for Pt rose from 20.1 t in 1998 to 72.7 t in 2015. During this period, it consumed a total of 862.5 t Pt, with 718.9 t of this in jewelry. In comparison, the autocatalytic sectors in the ER and the NAR are larger in terms of Pt consumption. Growth in global production is observed from 78.7 t in 1975 to 212.4 t in 2006, yet to 2013, annual production dwindled to 178.5 t owning to the global financial crisis in 2008 and its aftermath (Mudd et al., 2018)

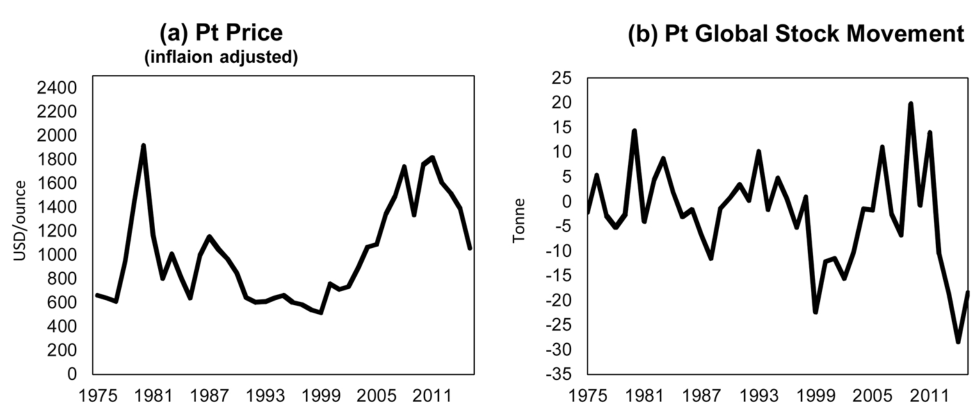

Fig. 10. (a) Pt price (inflation-adjusted) from 1975 to 2015; (b) global stock movement during this period.

3.3.2. Platinum price and global stockpiling behavior (SK)

The inflation-adjusted price of Pt from 1975 to 2015 is shown in Fig. 10(a). Of note is that the price surge from 1999 to 2008 coincides well with (1) the strong growth in global consumption for autocatalytic applications during the same period (Fig. 9(a)), (2) the decrease of Pt consumption in the global jewelry sector (Fig. 9(b)), (3) the growth of Pt consumption in the ER and China (Fig. 9(c)), and (4) the rapid increase of Pt stockpiles worldwide (Fig. 10(b)). A positive stock movement at a given year indicates an increase in global stockpiling behavior during that year and vice versa. The global Pt stock movement generally follows a downward trend with strong seasonal components, suggesting that increasing volumes of Pt were released to the market during this period, despite seasonal variations. Fig. 10 also indicates increasing fluctuations over time, suggesting the intensification of the stockpiling-and-releasing behaviors.

3.4. Analysis of correlations

This section discusses the statistically-significant correlations found during the analyses of the constraint-variable correlations and the mutual-variable correlations in the Pt criticality system. Where possible, their causalities are also analyzed.

3.4.1. South Africa: social progress, Pt production, and price

As shown in Parts (a) and (b) of Table 3, the analyses using the ARDL indicate that while normalizing the impacts of other constraints, both the decrease of Pt production and the rise of Pt price in South Africa are associated with the increase of South Africa's HDI. Countries estimated to have a higher HDI tend to value the quality of life and environmental protection above the intrusive development of the mining industry (Graedel et al., 2012). Thus, the increase of HDI could lead to the reduction of mining intensity, which negatively affects the mineral production rate and the price. In South Africa, primarily in the platinum belt of the Bushveld region, tensions between the desire for better living standards and Pt production have tightened. Historically, under the influence of colonialism, mine workers suffered from low wages, poor working conditions, and unfair pension rates. Members of rural communities, such as farmers near mining operations, have endured forced land sales and impacts from groundwater pollution. In recent years, communities mobilized to lead a five-month strike in 2012 and riots at Marikana in 2014 (Cairncross and Kisting, 2016). These incidents have been documented to severely disrupt Pt production in the region and indirectly affect the Pt price (JM, 1975-2019JM, -, 2019JM, 1975-2019). As a result, we argue that Pt production and price are affected by the level of social progress in the region, which adds a layer of causality to the newly discovered statistical associations.

3.4.2. Pt consumption, production and price

Using ARDL, we found that Pt prices are positively associated with Pt production from South Africa, but are not associated with Pt production from the NAR (excluding Mexico) and Russia with statistical significance. We also found that Pt prices are positively associated with consumption in the NAR but not in other regions. These results are shown in Table 3 (parts (c) and (d)). We acknowledge that the price analysis is more complicated than examining the statistical associations between price, consumption, and production. Other factors such as short-term market disruptions and market mood could also play significant roles. Thus, it is difficult to draw conclusions about the causality of these statistical relationships. However, it can be said with reasonable confidence that Pt price is more connected with Pt production from South Africa than that of the NAR (excluding Mexico) and Russia. This is likely due to South Africa's dominance in both reserves and supply, but may also be linked to differences in the PGM ore concentration ratio of Pt to palladium (Pd). The PGM ore concentration ratio of Pt to Pd differs significantly by regions/countries. In South Africa, especially the Eastern and Western Bushveld, ores are Pt dominant; whereas PGM ores in other parts of the world such as the Noril'sk-Talnakh field in Russia are Pd dominant (Mudd et al., 2019). In terms of consumption, we find that Pt price is more connected with consumption in the NAR than in other regions.

We, we also find that, while normalizing the influence of Pt production from the NAR (excluding Mexico) and Russia, production from South Africa in period t is positively associated with the consumption from the NAR in period $t-1$ and consumption from Japan in period t with statistical significance Table 3 (e). On the other hand, we only find statistically significant associations between Pt production from South Africa and consumption in the NAR. Given that this association is time-lagged, one could potentially be a leading predictor to the other, i.e., there exists a *Granger causality* between them.

3.4.3. Pt global stock movement and its global supply concentration

We found that Pt global stock movements are positively associated with the Pt national CR3 index while normalizing the impact of other variables such as the price, suggesting that the increase of Pt stockpiling intensity worldwide is associated with increases in Pt global supply concentration (Table 3 (f)). A reasonable interpretation regarding the causality of this correlation would be that the increase of the supply concentration leads to a higher level of stockpiling intensity. While it is difficult to imagine that the changes of stockpiling intensity could reasonably affect the Pt supply concentration, the reverse could happen if Pt buyers and sellers wish to stockpile more Pt as strategic reserves when Pt supply concentration ↓ a prominent component of Pt supply risk ↓ increases.

4. Conclusions and future work

Our systems approach to criticality presents mineral criticality in a time-dependent and interactive manner. The components of our framework include various supply-risk drivers, vulnerability aspects, market dynamics, and their statistical relationships. Based on this framework, we constructed the criticality system for Pt. We also evaluated (1) six drivers of Pt global supply risk, (2) five aspects of Pt vulnerability in the context of the ER, the NAR, Japan, and China, (3) five market variables, and (4) their statistically significant interconnections.

Our results demonstrated that the combination of South Africa's socio-political status and its dominance over global Pt supply (and reserves) contributes significantly to the risks of a global Pt supply disruption. The geological availability of Pt is less of a factor here. We also find that Pt production in South Africa appears to be directly affected by the level of social progress in the region, whereas Pt prices appear to be indirectly affected. This price is more connected with consumption in the NAR than in the ER, Japan, and China. In terms of supply, price is more connected with Pt production from South Africa than that of the NAR (excluding Mexico) and Russia. However, Pt has greater economic importance to the ER and China than to Japan and the NAR. The ER is at a higher level of vulnerability to Pt supply restrictions when comparing its NEI of Pt, its Pt consumption structure, its Pt import reliance, and its PSPII to others. Pt consumption in the NAR could potentially be a leading predictor of Pt's production from the only dominate supplier ↓ South Africa.

Naturally, there are uncertainties in the data acquired which could affect the precision of the analyses. The availability of data has also been a challenge. To the best of our ability, adequate measures, such as data cross-referencing and seeking the experts' advice, have been taken to ensure the quality of the data. The criticality system of Pt developed in this study can be further improved by including more aspects of Pt supply risk, the vulnerability, and market dynamics at a finer time-series resolution. However, more datasets need to be available. For the further improvement of the general criticality-system framework, it would be beneficial if the improved framework can simultaneously assess a metal's criticality in both the *mineral-focused* dimension and the *peer-focused* dimension. In other words, the improved framework

Table 3
The statistically significant correlation results of using the ARDL.

Responses Variable	Input Variables	Gradient	p-value
(a) South Africa production in tonne (period ***t***)	South Africa PPI (period t)	–	–
	South Africa PPI (period $t-1$)	–	–
	South Africa HDI (period t)	−3372	0.064
	South Africa HDI (period $t-1$)	–	–
	South Africa WGIPV (period t)	–	–
	South Africa WGIPV (period $t-1$)	–	–
	South Africa Production in tonne (period $t-1$)	–	–
	South Africa Production in tonne (period $t-2$)	–	–
(b) Pt price in USD/ounce (period ***t***)	South Africa PPI (period t)	–	–
	South Africa PPI (period $t-1$)	–	–
	South Africa HDI (period t)	7280	0.024
	South Africa HDI (period $t-1$)	–	–
	South Africa WGIPV (period t)	–	–
	South Africa WGIPV (period $t-1$)	–	–
	South Africa Production in tonne (period $t-1$)	–	–
	South Africa Production in tonne (period $t-2$)	–	–
(c) Pt price in USD/ounce (period ***t***)	the NAR Region (excluding Mexico) production (period t)	–	–
	the NAR Region (excluding Mexico) production (period $t-1$)	–	–
	Russia production (period t)	–	–
	Russia production (period $t-1$)	–	–
	South Africa production (period t)	19.22	0.023
	South Africa production (period $t-1$)	–	–
	Pt price in USD/ounce (period $t-1$)	0.441	0.010
(d) Pt price in USD/ounce (period ***t***)	the NAR Region consumption in tonne (period t)	17.080	0.023
	the NAR Region consumption in tonne (period $t-1$)	–	–
	The ER consumption in tonne (period t)	–	–
	The ER consumption in tonne (period $t-1$)	–	–
	Japan consumption in tonne (period t)		
	Japan consumption in tonne (period $t-1$)	–	–
	Pt price in USD/ounce (period $t-1$)	0.441	0.010
(e) South Africa production in tonne (period ***t***)	the NAR Region consumption in tonne (period t)	–	–
	the NAR Region consumption in tonne (period $t-1$)	0.612	0.053
	The ER consumption in tonne (period t)	–	–
	The ER consumption in tonne (period $t-1$)	–	–
	Japan consumption in tonne (period t)	0.485	0.032
	Japan consumption in tonne (period $t-1$)	–	–
	the NAR Region (excluding Mexico) production (period t)	–	–
	the NAR Region (excluding Mexico) production (period $t-1$)	–	–
	Russia production (period t)	–	–
	Russia production (period $t-1$)	–	–
	South Africa Production in tonne (period $t-1$)	–	–
	South Africa Production in tonne (period $t-2$)	–	–
(f) Pt stock movement in tonne (period ***t***)	Pt's national level CR3 index (period t)	3.159	0.097
	Pt's national level CR3 index (period $t-1$)	–	–
	Pt price in USD/ounce (period t)	–	–
	Pt price in USD/ounce (period $t-1$)	–	–
	Pt stock movement in tonne (period $t-1$)	–	–
	Pt stock movement in tonne (period $t-2$)	–	–

*All variables used have been de-trended.
*The number of lags considered depends on autocorrelation analyses.

should be able to determine how critical a metal is to a specific end user compared to other metals while being able to assess how critical the metal is to the end user compared to other end users of this metal. Through the dynamic evaluation of Pt criticality, this study has demonstrated an important step toward more comprehensive assessments of mineral criticality evaluation in the future.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104532.

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