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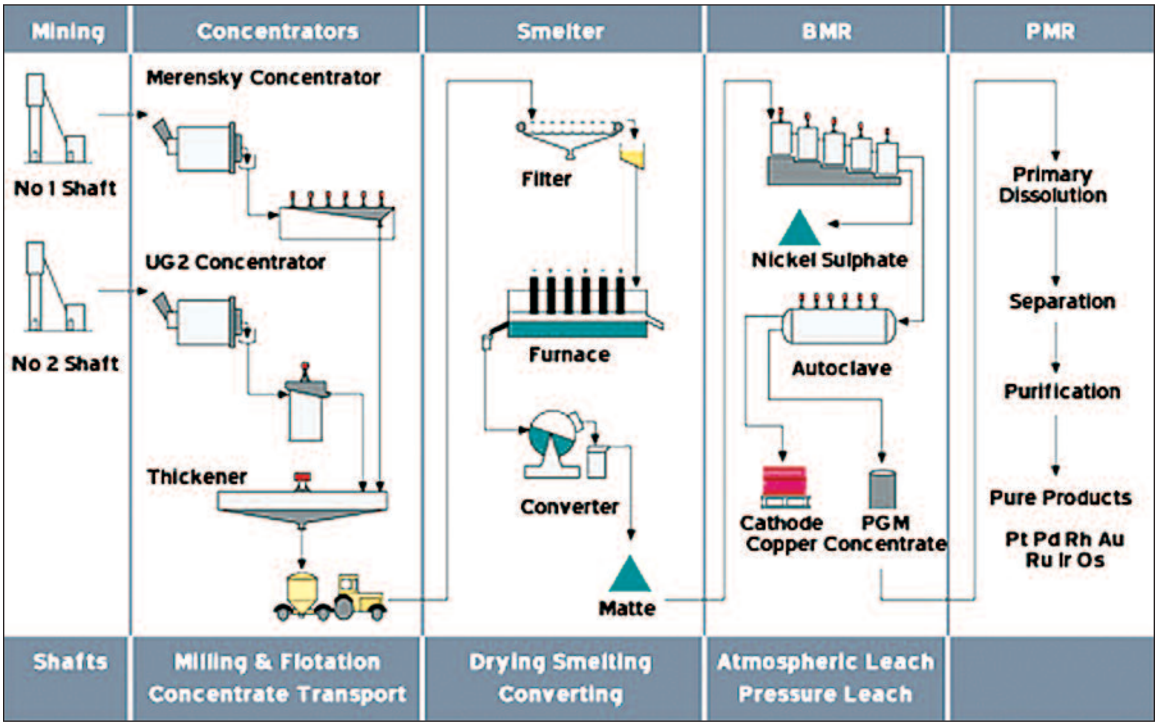

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ABSTRACT

Platinum is a strategic resource for the world economy and appears to be unsubstitutable in many of its uses. As a consequence, establishing its life cycle and quantifying net increases and decreases may serve as a basis for detecting lifecycle-wide opportunities for increasing recycling and reuse of platinum. With this aim, we have characterized the platinum cycle for the Russian Federation for the year 2000. It was found that most of the platinum produced in Russia was exported immediately (21,300 kg Pt/yr (82%)), while the remainder was stockpiled (2,200 kg Pt/yr (8.5%)) or used domestically (2,450 kg Pt/yr, (9.4%)). Russia has a continuing reliance on fabricated platinum imports (1,600 kg Pt/yr). Recovery of platinum from waste and scrap is undeveloped, although there are significant domestic sources, particularly the military sector.

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INTRODUCTION

An important feature of sustainable development is the comprehensive management of anthropogenic resource flows, management based on accurate accounting of all materials that enter economic and environmental systems, are generated and accumulate within these systems, and exit these systems in various forms [6, 29]*. This is particularly critical for resources that are irreplaceable components in industrial cycles of high-tech industries such as electronics, medical equipment, chemicals, automobiles, aviation, and energy generation, refining, and processing. The depletion of the sustaining source of supply of technologically strategic materials creates a potential limit for sustainable economic development [5, 49].

Characterization of the cycles of metals widely used in technology is the task of the Stocks and Flows Project at Yale University. This work is particularly important for materials in short supply or for which rates of use are rapidly increasing.

From this standpoint, platinum is a resource requiring considerable attention. Platinum's unique physical and chemical properties, even within the platinum group of metals, make it irreplaceable in a myriad of industrial applications – particularly the chemical processes involved in catalysis of anticancer drugs, pollution control, and fuel cells.[1] As a result, platinum is classified and controlled as a strategic metal in many countries [19]. Tracing the stocks and flows of anthropogenic platinum on local, national, and global levels is an important step toward developing appropriate approaches for better management of this metal throughout different industries from the prospective of long-term sustainability [27].

The extraction, processing, and use of platinum have geopolitical as well as technological aspects. Presently, the U.S., Japan, the U.K., Germany, and China are the world's dominant consumers of platinum; South Africa and Russia, however, are the largest producers of this metal [9]. As a consequence, platinum stocks and flows move largely among a small number of countries and have the potential to be disrupted by political considerations.

* Throughout the paper, numbers in brackets refer to works cited, listed starting on page 25.

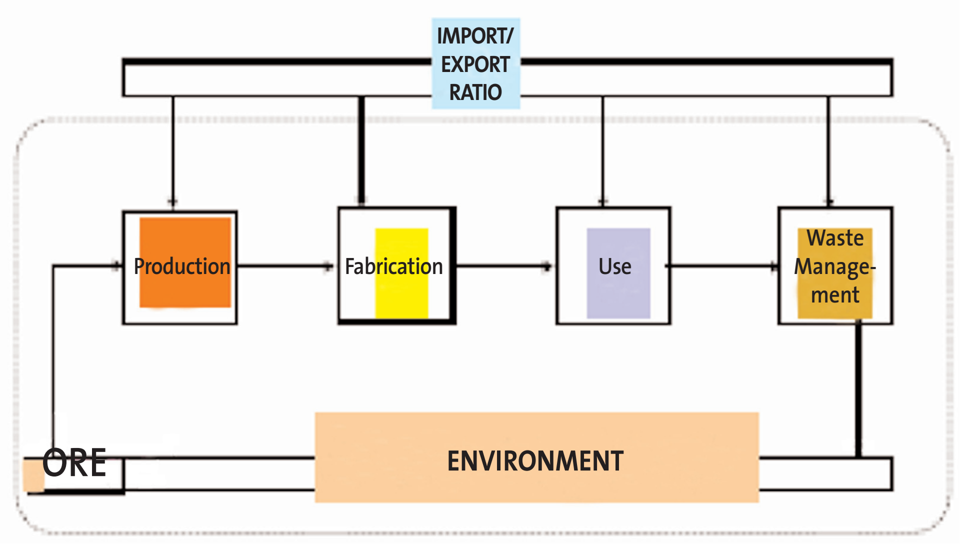
[1] In order to perform the fuel cell EV assessment, Räde et al. made scenarios of demand for platinum for manufacturing fuel-cell vehicles. In the baseline scenario, the demand for platinum is estimated at 67 Gg of platinum and current reserves would be depleted in the 2050s [64].

THE MATERIAL FLOW ANALYSIS APPROACH

In examining the driving forces behind environmental issues, especially those that cross national boundaries, the IPAT model is often employed. IPAT sees environmental impacts (I) as a function of the size of human population (P), affluence and consumption patterns (A), and technology (T) deployed to meet perceived needs [23, 29, 78]. Material Flow Analysis (MFA) is one of the analytical tools that can be successfully used to address A and T in the IPAT equation. Furthermore, MFA goes beyond traditional material accounting systems, looking primarily at supply in terms of natural resources, and at use in terms of initial input to the industrial economy. MFA is similar to economic material accounting, used for quantifying transactions between various sectors of the economy.

The Material Flow Analysis approach is based on computing all inputs, stocks and outputs in various metal life stages, as shown in Figure 1. Through this framework, the flows of industrial materials are examined through the stages of Production, Fabrication and Manufacturing, Use, and Waste Management [4, 28].

Figure 1 Major Cycle Reservoirs and Flows: the six-reservoir cycle for a typical industrial material



Source: T. E. Graedel *et al.*, 2003 [28].

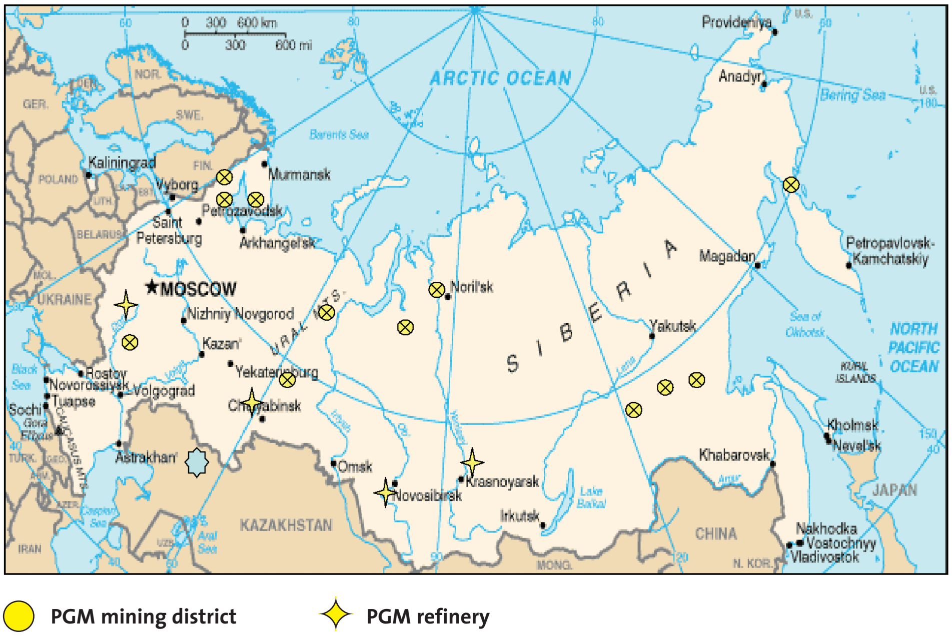
OBJECTIVE AND SYSTEM BOUNDARY FOR THIS STUDY

The main purpose of the present work is to demonstrate that accounting for the industrial cycles of different products containing one common component – from extraction of raw materials, to transformation into intermediate goods, to consumption of final products, to waste utilization – is a principal tool in achieving both economic and environmental efficiency through technological innovation. Moreover, for materials that are strategically meaningful for sustainable development, the result can serve as a benchmark for further analysis at the regional or global level.

Having a comprehensive budget for platinum, reflecting all inputs, stocks, and outputs in end-user industries, is critical for sustaining many modern economic sectors. We chose the Russian Federation, the largest producer of platinum on the Eurasian continent and one of only two major sources of platinum, as the basis for our case study on the determination of the platinum cycle.

Primary platinum production within the Russian Federation comes from eleven platinum-group metal (PGM) mining deposits and four refineries (Figure 2). The largest volume of platinum produced is mined as a byproduct from nickel-copper deposits in the Taimyr Peninsula, above the Arctic Circle. Alluvial operations (the extraction of minerals from glacier-deposited particles) in the Far East of Russia also supply significant quantities of platinum. Deposits in the Urals, which are not now in production, represent a strategic source of platinum for the future [11].

Figure 2 Map of Russian platinum group metal (PGM) districts



We evaluated platinum flows for the year 2000, when substantial information became available for the first time.[2] It must be mentioned that the world platinum market in 1999-2000 was even more volatile than usual. The price for platinum group metals increased from 45%-219% for different PGMs, reaching a record high price and resulting in an increased demand for platinum as a substitute for other PGM group metals [43]. For Russian platinum, the year 2000 was a turning point for political reasons: the central government relinquished total control over the sale of platinum and permitted direct sales by Russian producers to markets outside of the country.

[2] Before 2000 the Russian government (Ministry of Natural Resources, Almazjuvelirexport, Gokhran and Goscomtat) and the platinum producers were the dominant owners of information about how much platinum was mined, refined, exported, and imported. The Russian central bank was the main holder of platinum stocks. Starting from the year 2000, the principal Russian government trading agency, Almazjuvelirexport, was closed and producers were given fixed open quotas and export licenses for their products.

Overall, the year 2000 was the first year when sufficient data became available to enable analysts to begin characterization of the Russian platinum cycle.

INDUSTRIAL PLATINUM CYCLE – PRODUCTION PHASE

The production phase of the platinum industrial cycle is the most resource- capital- and energy-intensive stage of the metal's life cycle [6, 44]. In 2000, approximately 26,000 kg of platinum was produced in Russia, requiring extraction of at least 5000 Tg of non commercial ore (1 Tg = 10^{12}g)[96]. Underground deposits are the main source of platinum, accounting for over 75% of the total amount of platinum produced. Alluvial placers supply the remaining approximate 25%. Platinum entering the production phase is in the form of ores such as cooperite (Pt, Pd, Ni)S, yixunite (Pt_3In), damiaoite ($PtIn_2$), braggite (Pt,Pd,Ni)S, and hongshiite (PtCu) [1].

Nickel-copper ores, the most common platinum-containing ores in Russia, from which platinum is produced as a by-product, are mined from underground deposits and concentrated via a series of processes that include crushing, grinding, flotation, and magnetic separation. The concentrates are smelted to a converter matte and refined to yield the high quality platinum. There are some losses of platinum caused by processing of the pyrothotite milling fractions, which pass directly into the tailings, and by the splitting of the ore concentrates [68].

Refining platinum from nickel and copper electrolytic slimes involves roasting, leaching with sulfuric acid, melting and casting into anodes, and electro-refining. Losses of platinum in the form of complex halogenated salts of platinum are associated with the later steps of the refining operations [1].

The production of platinum from alluvial deposits includes washing and gravity separation stages to concentrate platinum grains. Platinum concentrates are then dissolved in hydrochloric and nitric acids and these solutions are electro-refined. Alluvial ores containing platinum are usually enriched by high concentrations of iron, which decrease the purity of the platinum grains separated from non-commercial ores. Archaic technology is the main reason for platinum losses in this stage [11].

The final outputs of the production phase are platinum ingots, platinum sponges[3], pellets, black powder of platinum, platinum grains, and nuggets [90, 91, 96].

The net balance of the industrial platinum cycle in the production phase (see also Table 2) was calculated according to Equation 1:

Equation 1 Net balance of industrial platinum cycle: production phase

$$F_P\,[Pt_{refined,outflow\,(2000)}] = F_P\,[Pt_{\mathrm{mined},undground\,(2000)}] + F_P\,[Pt_{\mathrm{mined},alluvial\,(2000)}] +$$

$$\sum_{i=1}^{n} F_P\,[Pt_{import\,(2000)}]_i - \sum_{i=1}^{n} F_P\,[Pt_{export\,(2000)}]_i - F_P\,[Pt_{tail,alluv\,(2000)}] -$$

$$- F_P\,[Pt_{tail,underg\,(2000)}] - F_P\,[Pt_{air\,(2000)}] - F_P\,[Pt_{stockpiles\,(2000)}]$$

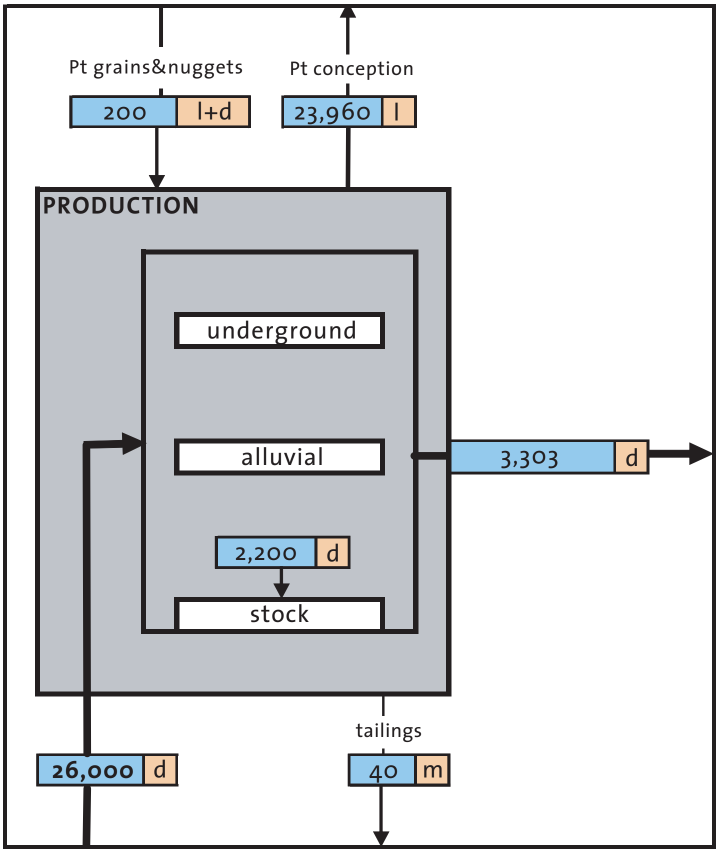
---

[3] Platinum sponge is metallic platinum in a gray, porous, spongy form, obtained by reducing the double chloride of platinum and ammonium. It absorbs oxygen, hydrogen, and certain other gases to a high degree, and is employed as an agent in oxidizing [1]

Table 2 Production Phase: Values of Equation 1 Variables

Variable	Definition	Value (kg Pt/yr)	Reference
$F_P\,[Pt_{refined,\,outflow\,(2000)}]$	Platinum generated in the Production Phase for further domestic use	2445	[Equation 1]
$F_P\,[Pt_{\mathrm{mined},\,undground\,(2000)}]$	Platinum produced from underground deposits	22800	[68], [95], [96]
$F_P\,[Pt_{\mathrm{mined},\,alluvial\,(2000)}]$	Platinum produced from alluvial deposits	3200	[68], [95], [96]
$\sum_{i=1}^{n} F_P\,[Pt_{import\,(2000)}]_i$	Platinum exported in the form of refined and non-refined products, where i n are symbols of countries-exporters	0	[67], [91], [92], [95]
$\sum_{i=1}^{n} F_P\,[Pt_{export\,(2000)}]_i$	Platinum imported in the form of refined and non-refined products, where i n are symbols of countries-exporters	21295	[50], [71], [84], [95]
$F_P\,[Pt_{tail,\,alluv\,(2000)}]$	Platinum in tailings of alluvial deposits	40	[1], [8]
$F_P\,[Pt_{tail,\,underg\,(2000)}]$	Platinum in tailing dumps of undergound deposits	20	[51], [68], [79]
$F_P\,[Pt_{air\,(2000)}]$	Platinum in the form of different compounds emitted to the air in refineries	<0.1	[48]
$F_P\,[Pt_{stockpiles\,(2000)}]$	Platinum transferred to stockpiles	2200	[95]

Figure 3 Platinum industrial cycle: production phase



Abbreviations: l – based on literature; d – calculated by difference; m – calculated by empirical model. Units are kg Pt/yr.

Figure 3 illustrates the results – that in the production phase, 23,960 kg of platinum is exported, 200 kg is imported, 3,303 is transferred to the following phase, and 40 kg is lost. Transnational platinum flows take place in the form of export trade in the year 2000. Over 90% of produced platinum leaves the system boundary through export overseas to nearly 20 countries. In particular, there are four countries importing over 60% of platinum of the total trade flow from the Russian Federation (the U.S.A., Switzerland, Germany, Republic of Korea and Japan), eight countries accounting for consumption of 20-60% of Russian platinum output, and four countries for the remaining [92].

Knowledge in the field of precious metals traditionally tends to flow along organizational lines, with little sharing of information. However, data used for calculating $F_P[Pt_{refined,outflow(2000)}]$ in the present work has been cross-checked with data from the U.S. Geological Survey, Johnson Matthey, UN Comtrade, British Geological Survey, CMC Group, Rockwell Group, Platinum Guild International and other organizations.

INDUSTRIAL PLATINUM CYCLE – FABRICATION AND MANUFACTURING PHASE

Platinum leaving the production phase proceeds to the fabrication and manufacturing phase, in which it is transformed into intermediate products. Platinum entering this phase comes from three sources: domestically produced platinum, imported semi-manufactured platinum, and platinum obtained from recovery and recycling of waste and scrap [16].

Fabrication of platinum refers to the production of "semi"– products that can be used in various industries without further processing, such as platinum wire, anodes, cathodes, rods, briquettes, and bars. Some of these products are exported as traded commodities. The remaining amounts of platinum enter domestic manufacturing.

The manufacture in the Russian Federation of platinum-based catalysts used to control emissions from automobiles started growing in the late 1990s, and the production of platinum-based catalytic converters in 2000 increased by 11% compared to the previous year [53]. But within Russia, there is little technological capacity to produce high quality platinum products suitable for applications in high-tech industry.[4] This low capacity, combined with economic recession in the CIS in 2000, resulted in only small amounts of platinum being used in the fabrication and manufacturing phase.

Platinum flow to fabrication and manufacturing from the recovery and recycling of waste and scrap are usually unaccounted for in formal trade statistics.[5] It is probable that small amounts of platinum are obtained from recovery and recycling within Russia. There is no institutionalized scheme for secondary recovery of platinum, and there is no coordinated network of recycling facilities.[6] However, the potential for recovery of PGMs is high: metals may be recovered from a wide range of scrap, including chemical process catalysts, petroleum refining catalysts, electronic equipment, old jewelry, old thermocouples, crucibles, and other equipment. In particular, the Russian military and the military supply industry account for large amounts of platinum, and it is estimated that 16 Mg of platinum can be recovered from military electronic scrap [69].

The net balance of the industrial platinum cycle in 2000 in the fabrication and manufacturing phase (Equation 2) is calculated as the difference between the amounts of platinum materials that entered the fabrication and manufacturing phase and the amounts generated and manufactured within the fabrication and manufacturing phase (Table 3).

Equation 2 Net balance of industrial platinum cycle: fabrication and manufacturing phase

$$F_{FM}[Pt_{outflow(2000)}] = F_{P}[Pt_{PP,refined,outflow(2000)}] +$$

$$+ \sum_{i=1}^{n} F_{FM}[Pt_{import(2000)}]_i + F_{WM}[Pt_{WMP,scrap(2000)}] - \sum_{1=i}^{n} F_{FWM}[Pt_{export(2000)}]_i$$

---

[4] Such production is based on a sequence of fine technological processes and modern analytical laboratory research that is not available or for which there has been little demand.

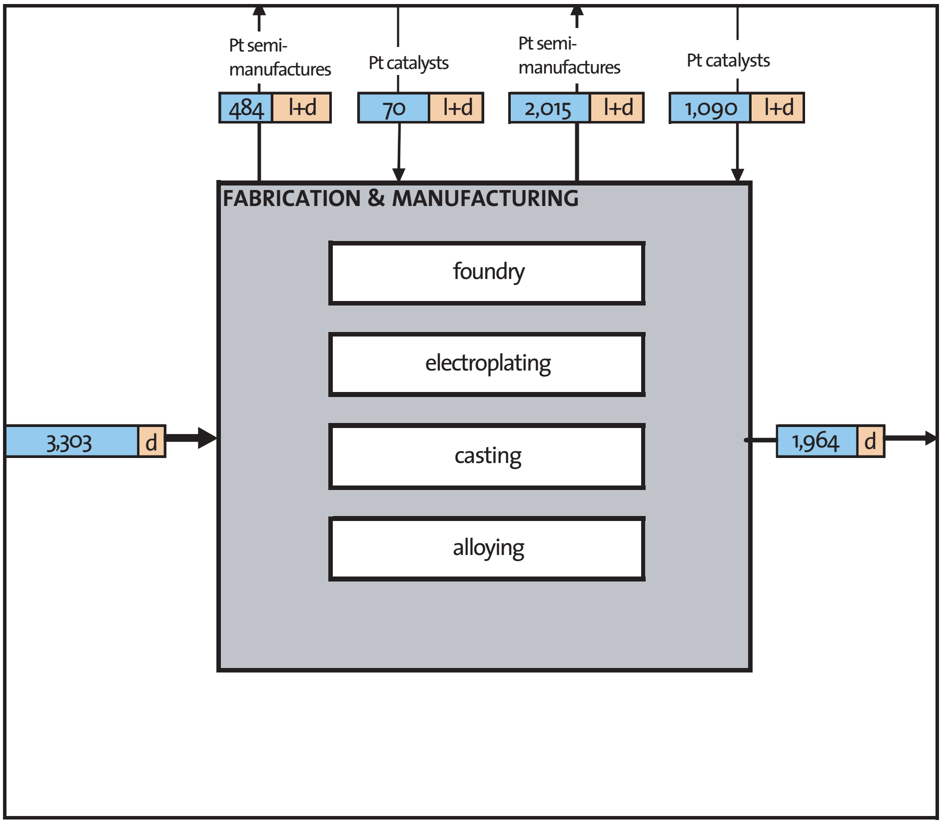
[5] Upstream industrial flow is a flow in the industrial cycle of materials opposite to the main flow of materials. Here it is a flow from the Waste Management Phase to the Fabrication and Manufacturing Phase.

[6] In the early 1990s, when the Soviet Union dissolved in a certain degree of disorganization, large volumes of military scrap were exported to the U.S.A. and Europe for recovery of precious metals, often without formal accounting to the Russian government or source agencies.

Table 3 Fabrication and Manufacturing Phase: Values of Equation 2 Variables

Variable	Definition	Value (kg Pt/yr)	Reference
$F_{FM}[Pt_{outflow\,(2000)}]$	Platinum generated in the Fabrication and Manufacturing Phase for further domestic use	1964	[Equation 2]
$F_{P}[Pt_{PP,\,refined,\,outflow\,(2000)}]$	Platinum generated in the Production Phase for further domestic use	2445	[Equation 1]
$\sum_{i=1}^{n} F_{FM}[Pt_{import\,(2000)}]_i$	Platinum imported in the form of platinum semi-manufactures and manufactures, where i n are symbols of countries-importers	1574	[67], [91]
$F_{WM}[Pt_{WMP,\,scrap\,(2000)}]$	Platinum in the form of waste and scrap generated in the Waste Management Phase	30	[50], [94]
$\sum_{i=1}^{n} F_{FWM}[Pt_{export\,(2000)}]_i$	Platinum exported in the form of platinum semi-manufactures and manufactures, where i n are symbols of countries-importers	2085	[1], [20], [68], [90]

Figure 4 Diagram of Platinum Industrial Flows: Fabrication and Manufacturing Phase Abbreviations: d – calculated by difference, l – based on literature. Units are kg Pt/yr.



In the fabrication and manufacturing phase, of the total amount of platinum, 2,085 kg is exported, 1,754 kg is imported and 1,964 kg is transferred to the following phase. Industrial platinum flows primarily in the form of wire cloth or grill. Overall, the transnational network includes 15 countries. The UK, Germany, and South Korea are major importers of semi-manufactured platinum products into Russia. Exported platinum metals flows from Russia end up primarily in Australia, China, and Italy.

INDUSTRIAL PLATINUM CYCLE – USE PHASE

In the Use Phase, platinum is in the form of either finished products or components of other products. The principal end-users of platinum within Russia are the petrochemical industry, the chemical industry, the electric and electronic industries, the jewelry industry, the automotive industry, the steel industry, the medical industry, the glass industry, and the aviation industry.[7]

Petrochemical Industry

In the petrochemical industry, platinum catalysts are used to upgrade naphthas into high-octane petrochemical feedstocks, in the dewaxing of lubricating oils, and in the de-aromatization of diesel fuel [8, 68]. Within Russia, the phase-out of lead in gasoline forced oil refining facilities to produce unleaded gasoline with a high-octane level (RON 95 and 93). To reach this target, it was necessary to replace the existing Russian catalyst AP-64 with 0.6 weight per cent platinum catalysts [2]. In particular, a new platinum-rhenium (Pt:Re=1:1) catalyst is now used nationwide in oil refineries in Russia, Belarus, and Uzbekistan [90]. Upgrading oil refineries also increased demand for platinum reforming catalysts. Platinum catalysts suspended on aluminum oxide, and platinum catalysts on a zeolite base, are used in reforming and isomerisation [41].

Some platinum is inevitably lost during use and handling at petroleum refineries. In particular, in the U.S. around 8,000 kg of platinum catalysts was lost in oil refining processes in 2000 [1, 68, 19, 67]. In 2000, the operating refining capacity in Russia accounted for 123 million tons of oil, which, using the same loss ratio, would have resulted in consumption/loss of at least 1230 kg of platinum catalyst. In addition, the low regeneration capacity of oil refineries, and a poorly developed network of industries providing toll regeneration[8] of spent catalysts, would have resulted in significant additional losses of platinum [1].

Jewelry Industry

The next largest market for platinum is the jewelry industry, including medals and commemorative coins. In 2000 Russian jewelry manufacturers utilized about 150 kg of platinum in platinum-containing goods. This assessment has been made by taking into account illegal suppliers of jewelry, estimated to account for 25-30% of Russia's jewelry market. In addition, the year 2000 was the 400th anniversary of the first issue of Russian coins, and at least 2 kg of platinum was released in the form of commemorative platinum coins [62].

Chemical Industry

The chemical industry is the next largest consumer of platinum, used in catalysis in the production of a variety of products [24, 37, 68]. This platinum is in the form of

[7] The industrial demand for platinum in Russia differs substantially from that in other parts of the world. In particular, the largest demand for primary platinum is in jewelry, followed by autocatalysts, and the chemical and electrical industries. Autocatalysts account for 21% of present and 30% of cumulative demand. Per capita use of primary platinum differs substantially among the industrialized countries, where the per capita use of primary platinum is extraordinary high in Japan [64].

[8] In the platinum industry there are three main sources of platinum supply: primary producers, secondary producers and toll producers (toll refining is refining for small producers that do not have their own smelters) [25].

wire, wire-gauze, foil, and colloidal platinum. Approximately 0.7g of platinum catalyst is utilized in the production of one ton of nitric acid, and even larger amounts of platinum are required for the production of silicon.[9] Other uses of platinum catalysts are for the production of oleum and hydrocyanic acid [30]. According to A-1 Specialized Services & Supplies, Inc., the total loss of platinum catalysts accounts for 20-25 kg per year per reactor [37]. It is assumed that obsolescent Russian technologies in the chemical industry are even more catalyst-intensive, and platinum lost in this production is not recovered. It was estimated for this paper that at least 50 kg of platinum was utilized by the chemical industry.

Glass Industry

In the glass industry, platinum and platinum-rhodium alloys are used for the production of high quality optical glass, which is further used for the manufacture of fiber optic cables, liquid crystal displays, and cathode ray tubes for televisions and computer monitors. Platinum is used in electrodes or components for furnaces, because it has high resistance to corrosion and heat and therefore does not require frequent replacement. It is also used in tanks, dies, and valves for fiberglass production, in crucibles for melting optical salt crystals, and in heater winding for glass. In Europe, by comparison, these uses require at least 800 kg of platinum per year [67, 68]. Even though the production of optical fiber for fiber optic communication systems in Russia in 2000 was not yet well developed, an estimated 30 kg of platinum was used in the production of crystal glass, cathodes, and other products.

Electronics Industry

In the electronics industry, platinum and platinum-rhodium alloys are used for the fabrication of semi-conductors, flat panel televisions, digital cameras, and plasma display panels [31]. One personal computer typically contains at least 0.01 g of platinum in the form of a platinum-cobalt alloy coating on the hard disk to increase its information storage capacity [37, 87]. The Russian electrics and electronics industry is small.[10] However, it is expected that a program launched by the federal government, "Electronic Russia 2002-2010," will generate demand for at least 90 kg of platinum annually [13, 17]. In 2000, an estimated 3.3 million PCs were imported to Russia, which added at least 30 kg of platinum to the system [39].

Automotive Industry

In the automotive industry, the main consumers of platinum are foreign carmakers, who respond to U.S. and European emission control legislation [22, 47]. Cars powered by petrol engines are fitted with a three-way catalytic system containing a platinum-palladium-rhodium mix to oxidize hydrocarbons and CO and to reduce NO_x [10]. Cars powered by diesel fuel generate fewer pollutants in the exhaust gas, and therefore less platinum coating is required; nonetheless, there is a diesel catalytic converter containing platinum catalyst on a ceramic substrate, and only platinum can be used for this purpose because of higher exhaust temperatures. At least 150,000

[9] In particular, export of nitric acid and sulphonitric acid from Russia to the World accounted for 18 metric tons [89], and export of silicon > 99.9% pure accounted for almost 70 metric tons kg in 2000 [93].

[10] Small Russian computer manufacturing such as Commend, NTP, and the MM-Company are insignificant end-users of platinum in the electronics industry [38, 39, 66].

foreign cars were imported to Russia in 2000, and 80,000 were domestically produced, which generated flows of platinum into use of 225 kg and 120 kg, respectively [7].

Steel Industry

In ferrous metallurgy, platinum is used as a component of thermocouples for temperature measurements. In particular, in the steel industry 13% rhodium-platinum wires 0.5 mm in diameter are used in thermocouples [3]. According to the International Iron and Steel Institute, Russia is fourth in steel production in the world. It is estimated that 200 kg of platinum is required to monitor the production of the 60 million metrics tons of steel produced in Russia in 2000.[11]

Medical Industry

In the medical industry platinum has many applications.[12] However, the application of sophisticated and expensive medical technologies in Russia is not widespread, and thus the use of platinum in the medical industry in Russia accounts for sustained, but insignificant, amounts of metal.[13] It was estimated that, with the import of dental alloys and catheters, 40 kg of platinum was added to the system and 20 kg was exported in the form of medical products in 2000. It is assumed that there are some losses to the environment in this industry, and it also must be mentioned that estimates given by the medical industry have a higher degree of uncertainty than in other industries.

Aviation Industry

The aviation industry in Russia is also a sustained but minor end user of platinum metals. According to the Russian Aerospace Agency, the industry is running at only 10-15% of capacity [46]. Nevertheless, production of jet engines is relevant to our study, as is the importation of aircraft, jet engines, turbo jets, aircraft replacement parts, and spacecraft. Russia is becoming heavily dependent on foreign aerospace equipment for its civilian airlines. The total import of platinum content aerospace components was low, because military technologies are subject to export restrictions in many countries. Russian exports of avionic products exceeded imports by a factor of three in 2000 [85].

Platinum aluminide 9.4 micron coating is used in hot section components in jet engines [46], and thus platinum is a necessary component of jet engine manufacture. In considering this use, as well as the import/export flows of jet engines and other avionic products, it is estimated that at least 20 kg of platinum was utilized by the aviation industry. Analyzing the demand for platinum by Russian aircraft manufacturers is, and will continue to be, a challenging task, however. It was estimated that in the next few years the use of platinum in aviation will be driven by the necessity to comply with the European Civil Aviation standards, which will require upgrading and replacing of most of the Russian aircraft fleet [34].

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[11] For comparison, Chinese production of 127 million metric tons of steel required 420 kg of platinum [33, 67].

[12] Platinum is a component of anti-cancer drugs such as cisplatin. In dental alloys platinum is used in a concentration range of 0.5-7% by weight [42, 68]. Platinum alloys are used for hypodermic needles and cautery points [3]. Platinum medical wire is used in surgical implants. There are also numerous applications of platinum in medical laboratory equipment – from crucibles for microanalysis to surgical instruments.

[13] For comparison, in Europe consumption of platinum solely for dental alloys accounts for at least 5000 kg per year [67].

Environmental Industry

In the environmental industry, platinum catalysts are used for the purification of gases, typically in the form of ceramic honeycomb monoliths or fixed beds of saddle catalysts used in air control technologies such as scrubbers and carbon adsorption systems [20]. Even though greenhouse gas emissions in Russia are much higher than the OECD average, the country's emissions are far below levels set for it by the Kyoto Protocol. It means that opportunities for application of platinum metals in the environmental industry within the system boundary are low. However, some amounts of platinum have been imported as components of greenhouse gas capture equipment. Platinum lost to the environment comes primarily from the transportation sector, where automobile catalytic converters are dispersing platinum compounds into the roadside media [12, 18, 48].[14]

The net balance of the platinum industrial cycle in the Use Phase is determined from Equation 3 (see also Table 4).

Equation 3 Net balance of industrial platinum cycle: use phase

$$
\begin{aligned}
&F_U\,[Pt_{outflow(2000)}] = F_{FM}\,[Pt_{outflow(2000)}] - F_U\,[Pt_{consumed(2000)}] - \sum_{i=1}^{n} F_U\,[Pt_{CI,consumed\,(2000)}]_i\ + \\
&mF_U\,[Pt_{GI,consumed\,(2000)}]\ mF_U\,[Pt_{JI,consumed\,(2000)}]\ mF_U\,[Pt_{EEI,consumed\,(2000)}] + \sum_{i=1}^{n} F_U\,[Pt_{EEI,import\,(2000)}]_i\ + \\
&- \sum_{i=1}^{n} F_U\,[Pt_{AI,consumed\,(2000)}]_i + \sum_{i=1}^{n} F_U\,[Pt_{AI,import\,(2000)}]_i\ mF_U\,[Pt_{SI,consumed\,(2000)}]\ \mathrm{m} \\
&\sum_{i=1}^{n} F_U\,[Pt_{MI,consumed\,(2000)}]_i + F_U\,[Pt_{AvI,consumed\,(2000)}] + \sum_{i=1}^{n} F_U\,[Pt_{AvI,import\,(2000)}]_i - \sum_{i=1}^{n} F_U\,[Pt,_{Av,export\,(2000)}]_i\ - \\
&- \sum_{i=1}^{n} F_{WM}\,[Pt_{environ\,(2000)}]_i + F_U\,[Pt_{military,stocks\,(2000)}] - \mathrm{F_U}\,[\mathrm{Pt}_{waste\,\&\,scrap\,(2000)}]
\end{aligned}
$$

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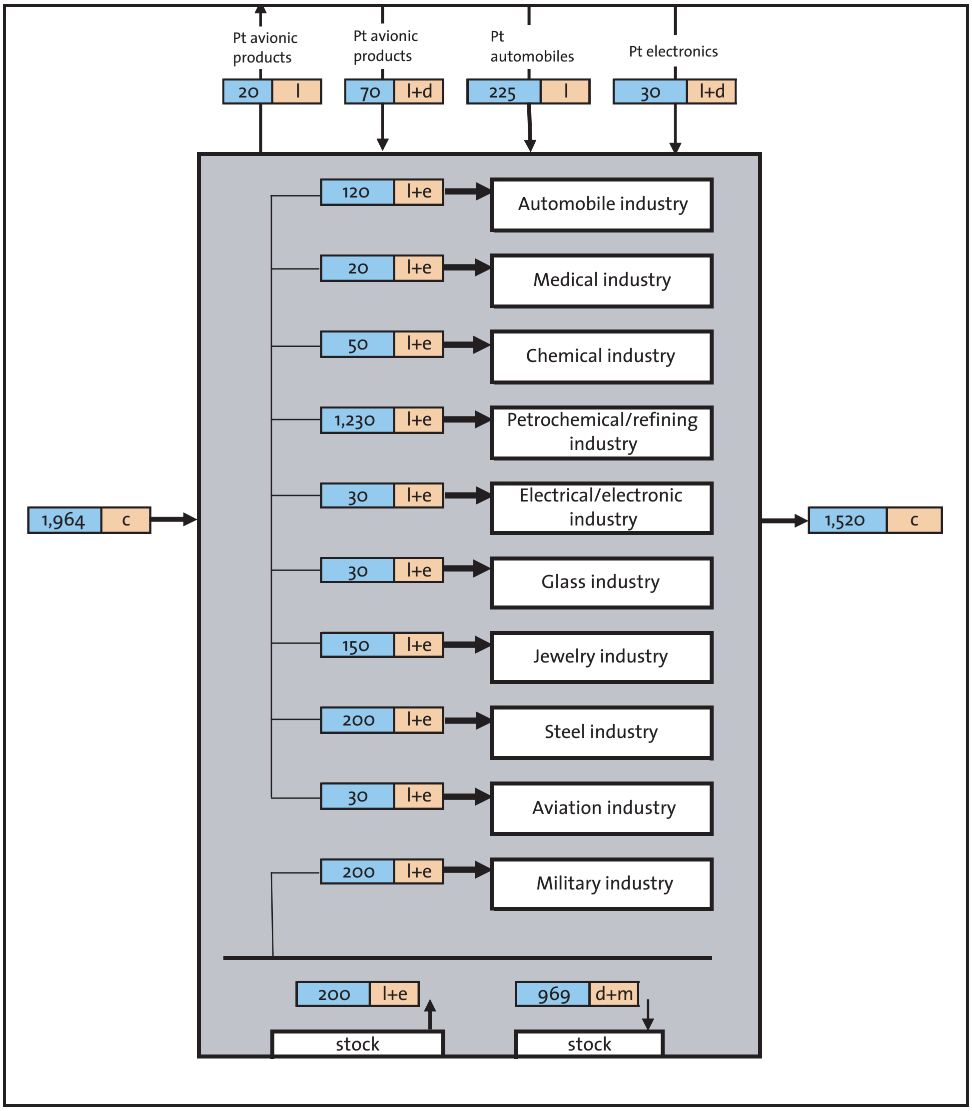
[14] Studies of platinum concentrations in roadside media have been conducted in Germany, U.K., U.S.A., Italy, and Western Australia. These studies show that the platinum content in road dust ranges from 420 ng/g to 500 ng/g. It was estimated that on average platinum is lost at a rate of 0.19 mg/km [54,59]. The lifetime of a platinum catalyst is 5 years (or 80,000 km). The amount of platinum released from catalytic converters depends on the speed of the motor vehicle, type of engine, age of catalysts, and type of fuel additives [60,61,62].

Table 4 Use Phase Values of Equation 3 Variables

Variable	Definition	Value (kg Pt/yr)	Reference
$F_U [Pt_{outflow\ (2000)}]$	Platinum generated in the Use Phase in the form of ready to use commodities	200	[Equation 3]
$F_{FM} [Pt_{outflow(2000)}]$	Platinum generated in the Fabrication and Manufacturing Phase for further domestic use	1964	[Equation 1]
$F_{U, Pt, PI, consumed\ (2000)}$	Platinum consumed by the Petrochemical Industry	1230	[8], [33], [42], [68], [85]
$F_U [Pt_{GI, consumed\ (2000)}]$	Platinum consumed by the chemical Industry, where i and n are symbols of different uses in the chemical industry	50	[30], [41], [83], [82], [71], [89], [9]
$F_{U, Pt, GI, consumed\ (2000)}$	Platinum consumed by the glass industry	30	[68], [88]
$\mathrm{F_U [Pt_{JI, consumed (2000)}]}$	Platinum consumed by the jewelry industry	150	[62]
$F_U [Pt_{EEI, consumed\ (2000)}]$	Platinum consumed by electric and electronic industry	5	[38], [39], [66], [68], [86], [87]
$\sum_i^n F_{U, Pt, EEI, import\ (2000)}$	Platinum imported in the form of electric and electronic products, where I and n are symbols of different country exporters	30	[7], [47]
$\sum_{i=1}^n F_U [Pt_{AI, consumed\ (2000)}]_i$	Platinum consumed by the automobile industry	120	[7], [22], [47]
$\sum_i^n F_{U, Pt, AI, import\ (2000)}$	Platinum imported as a component of automobiles, where I and n are symbols of different country exporters	225	[7], [47]
$F_U [Pt_{SI, consumed\ (2000)}]$	Platinum consumed by the steel industry	200	[68], [36], [35]
$\sum_{i=1}^n F_U [Pt_{MI, consumed\ (2000)}]_i$	Platinum consumed by the medical industry	40	[3], [68]
$F_U [Pt_{AvI, consumed\ (2000)}]$	Platinum consumed by the aviation industry	30	[68], [87]
$\sum_{i=1}^n F_U [Pt_{AvI, import\ (2000)}]_i$	Platinum imported as a component of avionic products, where I and n are symbols of different country-exporters	10	[34], [89], [46], [85]
$\sum_{i=1}^n F_U [Pt,_{Av, \mathrm{export}\ (2000)}]_i$	Platinum exported as a component of avionic products, where I and n are symbols of different country-importers	20	[34], [98], [46], [85]
$\sum_{i=1}^n F_{WM} [Pt_{environ\ (2000)}]_i$	Platinum lost to the environment	40	[12], [14], [18], [40], [43]
$F_U [Pt_{military, stocks\ (2000)}]$	Platinum supplied by the military industry	200	[55], [54], [70], [81]
$F_U [Pt_{waste \& scrap\ (2000)}]$	Platinum generated in the Use Phase in the form of waste and scrap	200	[55], [54], [70], [81]

Transnational flows of platinum generated in this stage form the most concentrated network of export and import trade flows. Industrial platinum stocks and flows in the Use Phase are illustrated in Figure 5. Overall, in the Use Phase, 295 kg of platinum is imported, 20 kg is exported, and 1,520 kg of platinum is transferred to the following stage.

Figure 5 Diagram of Platinum Industrial Flows: Use Phase. Units are kg Pt/yr



INDUSTRIAL PLATINUM CYCLE – WASTE MANAGEMENT PHASE

After a normal use life, each platinum product that is not in a dissipative form is transferred to obsolete waste and scrap. In the OECD, platinum waste and scrap are intensively recycled, and collectively are a major source of platinum. Because of the traditionally high market value of platinum, the major factor affecting recovery of platinum products from different types of wastes is their wide dispersal at very low concentrations [4, 5, 15].

Different sectors of the economy feed platinum materials to the waste management system in four distinct flows: Waste from electrical and electronic equipment (WEEE), industrial and hazardous waste (I&HW), Military Wastes (MW), and Sewage Sludge (SS) [26].

Industrial and hazardous wastes account for the largest portion of the platinum waste flows. The platinum flow of I&HW is mainly composed of spent platinum process catalysts, including automobile catalysts, and obsolete equipment containing platinum [40]. In particular, in the petrochemical and refining industries, heterogeneous catalysts containing platinum become fouled after about one year of use [60]. Thus, it is estimated that the amount of platinum lost in catalytic reforming was at least 1230 kg.

In the chemical industry, platinum catalysts are recycled according to production cycles that vary with the product and process. The amount of platinum that can be recovered from catalyst gauzes used during nitric acid production depends on such factors as the properties of the catalyst alloys, as well as operating and technical conditions. Given the rate of nitric acid production in Russia, at least 50 kg of platinum is estimated to have been available for recycling. The volume of platinum waste generated by the chemical industry annually in Russia might, however, be much larger than the amount we estimate based on publicly available sources of information (in particular, in the U.S., 2,300 kg of platinum waste from the chemical industry is collected through various filters and "gettering" devices for further recovery [32, 60]).

In the Russian glass industry, platinum is lost as a result of deterioration of equipment used for glass production and the deterioration of glass products themselves. However, the information currently available is insufficient to estimate the amount of platinum lost during the production of glass in Russia. The steel and aviation industries also supply some amounts of platinum to I&HW.

In the world, spent autocatalytic converters are the major source of secondary platinum for recycling [41]. Thus, in the U.S., about 25,500 kg of PGM from automobile catalysts is available for recycling annually.[15] These numbers still need to be determined for Russia, but it is clear that a recycling network for recovery of spent automobile catalysts has not yet been developed.

Electric and electronic equipment waste (WEEE) does not contribute a considerable amount of platinum to the system. WEEE is invariably recycled through copper smelting and electrolysis, and residues are then processed for the recovery of gold. Electrolytic gold cell slimes are periodically processed for PGM, from which some platinum is recovered. It is estimated that approximately 90% of the total WEEE flow is in use in offices, houses, second-hand markets, and repair stores.[16]

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[15] In general, the recycling potential of automobile converters is determined by the following factors: (1) the average loading of platinum in the converters; (2) the probability that cars from previous years will be taken out of service; (3) the proportion of platinum that is recoverable from a spent automobile converter [14, 25].

[16] In many countries, the WEEE recycling network is growing rapidly. In particular, in the U.S., 30% of the WEEE platinum scrap is being processed domestically, about 30% is shipped to collection centers to wait for more favorable conditions for processing, 20% is un-recovered, and the remaining catalytic converters are exported to Japan and Europe for processing [25].

Unlike other countries, demilitarization process waste is also on the list of the platinum waste flows in Russia. A nuclear-powered submarine contains approximately 20 kg of platinum used for igniting its nuclear reactor. Disbanding nuclear submarine divisions added at least 200 kg of platinum into the waste stream in 2000 [54, 55, 70, 89].

Sewage and sludge wastes (SS), in which platinum is primarily bound to non-fully metabolized chemicals, constitute the smallest source of platinum in the Russian waste stream. Because of the nature of the final products, these platinum materials are not available for recycling.

There are four main platinum flows that leave the waste management system: the recycling flow, the flow lost to the environment, the flow that enters landfills, and the export flow (Figure 6). Equation 4 was used to account for platinum flows in the waste management system (see also Table 5).

Equation 4

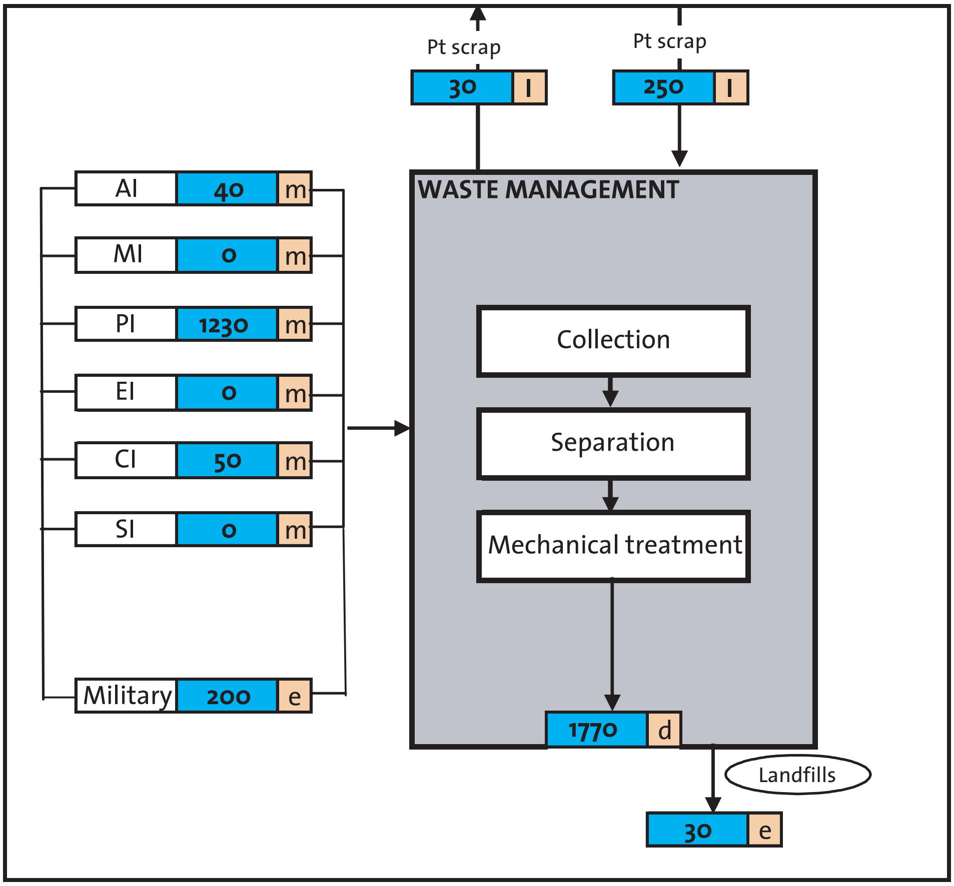
$$F_{WMP}[Pt_{WMP,\ stock(2000)}] = \sum_{i=1}^{n} F_{UP}[Pt_{waste(2000)}]_i + \sum_{i=1}^{n} F_{WMP}[Pt_{import(2000)}]_i + F_{WMP}[Pt_{military(2000)}] -$$

$$- \sum_{i=1}^{n} F_{WMP}[Pt_{export(2000)}]_i - \sum_{i=1}^{n} F_{WMP}[Pt_{environment(2000)}]_i - \sum_{i=1}^{n} F_{WMP}[Pt_{landfilled(2000)}]_i$$

Table 5 Waste Management Phase: Values of Equation 4 Variables

Variable	Definition	Value (kg Pt/yr)	Reference
$F_{WMP}[Pt_{WMP,stock\ (2000)}]$	refers to platinum accumulated in stocks in the Waste Management Phase	1710	[Equation 4]
$\sum_{i=1}^{n} F_{WMP}[Pt_{import\ (2000)}]_i$	refers to platinum imported in the form of platinum waste and scrap, where I,n are symbols of countries-exporters	250	[94]
$\sum_{i=1}^{n} F_{WMP}[Pt_{export\ (2000)}]_i$	refers to platinum exported in the form of platinum waste and scrap, where I,n are symbols of countries-exporters	30	[94]
$\sum_{i=1}^{n} F_{UP}[Pt_{waste(2000)}]_i$	refers to platinum in the form of waste and scrap generated in the Use Phase, where I,n are symbols of different industries	1520	[Equation 3]
$F_{WMP}[Pt_{military\ (2000)}]$	refers to platinum in the form of waste and scrap supplied by the military industry	200	[54],[55],[70],[81]
$\sum_{i=1}^{n} F_{WMP}[Pt_{landfilled\ (2000)}]_i$	refers to platinum accumulated on the landfills in the form of discarded platinum-containing products	30	[Equation 4]

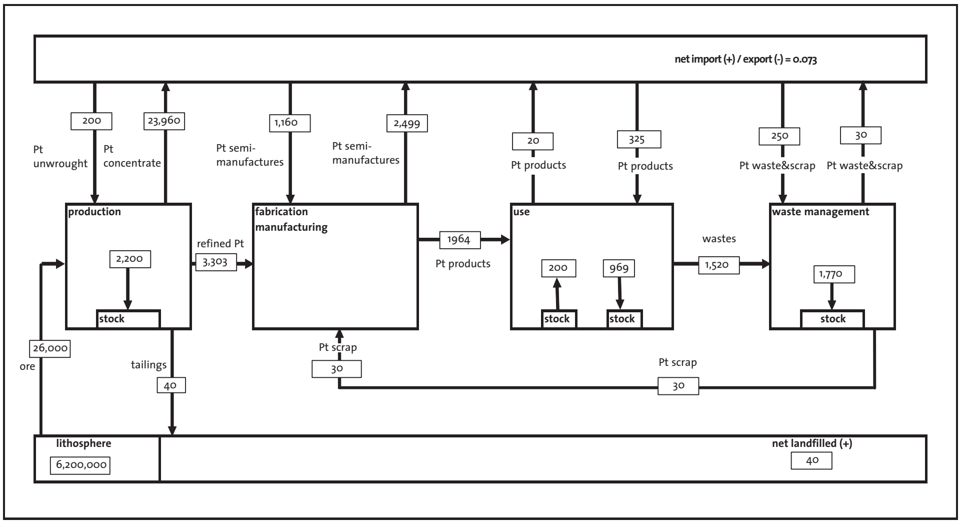
Figure 6 Diagram of Platinum Industrial Flows: Waste Management Phase. Abbreviations: c – closure balance, e – informed estimate, m – estimated by empirical model, l – based on literature. Units are kg Pt/yr.



In the Waste Management Phase, 1,520 kg of platinum comes from the Use Phase, 250 kg of platinum is imported in the form of waste and scrap, and 30 kg is lost to the environment. The great bulk of wastes and scrap containing platinum as a sole precious metal is imported from former republics of the Soviet Union and Latvia. Insignificant amounts are exported to a few countries, including the U.K., Germany, the United States, Switzerland, and other countries.

The overall Russian platinum cycle, produced by combining Figures 3-6, is shown in Figure 7.

Figure 7 The overall platinum cycle for the Russian Federation in 2000. Units are kg Pt/yr.



The material flow analysis we conducted for industrial platinum allowed us to identify three anomalies relative to global trends: a large discarded stock of platinum from the petrochemical and refining industry, a large flow of platinum from the military industry, and a high concentration of transnational platinum flows to a limited number of countries that depend upon platinum-bearing materials.

DISCUSSION

The increasing globalization of production can be a value-added factor for sustainable development and can contribute to the minimization of geopolitical instability, if all industrial material flows are optimally allocated among different industrial segments in a diverse set of geographical locations. Our material flow analysis shows potential resource-saving gains through better coordination of the complex interaction among the life-cycle stages of platinum.

Four stages related to industrial stocks and flows management of platinum in Russia have been described: production of raw materials, transformation of these materials into intermediate and finished products, distribution of these finished products to different end-users, and inventory of waste flows. The results are not, of course, perfectly accurate. A more precise picture could be achieved through improved monitoring of platinum flows coming from alluvial deposits, accounting for platinum losses in different operation cycles, and forecasting net decreases and net increases in platinum stockpiles.

In the context of looking for "win-win" approaches, the industry cycle conditions are favorable for the recovery of platinum products from different types of wastes. In Russia, platinum waste management is one of the least developed segments. Two major loss areas are essentially un-quantified: obsolete scrap from the automotive industry and from the steel industry. Data on platinum waste flow from the petrochemical industry, the military industry, and the chemical industry might be estimated, however. Obsolete industries, controversial laws (including past government ownership of all platinum), lack of adequate technologies, and an immature network of environmental organizations contribute to an inefficient waste management system in Russia. However, the potential niche market for platinum recycling initiatives is large.

As a starting point for integrated thinking and for understanding the strategic elements of sustainable industrial development, special attention should be paid to distinguishing between short-term and long-term environmental cost-saving strategies in the platinum sector [21]. In particular, demilitarization initiatives were a significant source of platinum supply in the year 2000; however, this flow has a highly time-limited period of intensity.

By contrast, petrochemical and chemical industries are the largest ongoing contributors to the loss of platinum from Russian industry. These platinum waste stocks have a high potential for recovery and subsequent return into the industrial cycle. [17] The Use Phase is the most geo-politically unstable stage of the industrial platinum cycle in Russia, which to a certain degree is also true for economies in other countries, due to high dependence on fluctuations in transnational and regional platinum flows. As a result of both intensifying environmental pressure and the globalization of production, more efficient management of platinum circulating in end-user industries is an important step in developing a forward-looking resource policy [80].

When thinking about technological innovation as a tool for decreasing environmental impact, this materials flow model can serve as a benchmark for integrating eco-efficient and resource-saving strategies in the decision-making processes of the public and private sectors.

[17] Catalysts in waste form used in the petroleum-refining industry can be deactivated by several different mechanisms, which primarily include decomposition of carbonaceous materials onto the catalyst surface during hydrocarbon processing at high temperatures [1].

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The Center for Industrial Ecology (CIE) at the Yale School of Forestry & Environmental Studies is dedicated to the promotion of research, teaching, and outreach in industrial ecology. The field is focused on the concept that an industrial system should be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems approach that seeks to optimize the total materials cycle–from virgin material, to finished material, to component, to product, to obsolete product, to ultimate disposal. The field is sometimes termed "the science and technology of sustainability."

Major foci at CIE include: 1) the Stocks and Flows Project, in which investigators are evaluating current and historical flows of specific materials like copper, estimating the stocks available in different types of reservoirs and evaluating the environmental implications; 2) the Industrial Symbiosis Project, in which multi-year research is being conducted primarily in Puerto Rico to establish the environmental and economic rationale for intra-industry exchange of materials, water, and energy; and 3) outreach and training focused on the environmental opportunities and challenges from the enormous expansion of Asian industrial activity, with the aim of institutionalizing the understanding and use of industrial ecology in Asia.

In addition to research, the Center for Industrial Ecology hosts national and international scholars, conducts master's, doctoral and postdoctoral study programs including a master's program in Industrial Environmental Management, and is home to the *Journal of Industrial Ecology*, the highly regarded journal of the International Society for Industrial Ecology.

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