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Dilemmas of mineral resources use in selected economic theories

Introduction

Natural resources – elements of the environment surrounding humankind – are of fundamental significance for human livelihood and economic development. Their condition and quality influence the level of satisfaction of various needs. Natural resources are usually divided into inexhaustible and exhaustible, with the latter further divided into renewable and non-renewable. Mineral resources occupy a particular place in the economic development of societies, determining the level of a society's well-being. They provide a high standard of living for contemporary societies, guaranteeing the satisfaction of energy and building material needs, and also constitute the basis of industrial and technical development (Shields 1998; Szamałek 2007; Gałuszka, Migaszewski 2009). In this view, they possess a strategic-technological meaning.

Abiotic mineral resources are counted among the non-renewable resources of the natural environment, i.e. those whose renewal does not occur within the span of a human lifetime, but whose regeneration is measured on a geological time scale. The classical school of economics, based on the concept of scarcity of resources, assumed that the availability of natural resources was limited and that it thus determined the upper limit of economic growth rates, and hence, in turn, the maximum attainable level of social well-being. The founders of the classical school (Malthus, Ricardo, Mill) proved the existence of an absolute limit of resources beyond which their further exploitation was impossible. The concept of inhomogeneity of resources was introduced, together with their division into better and worse categories. Better resources were used first; later, those characterized by inferior parameters

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were used as well. However, use of the latter was connected with the necessity of incurring higher costs in order to exploit them, thus increasing the costs of economic growth. Such thinking was inclined to assume a certain limit to economic growth beyond which no such growth could take place.

The basic premise of the neoclassical trend was the assumption of rationality in human actions. Rationalization of the behavior of a single member of the social system, expressed in maximizing his own satisfaction with meeting his individual needs, was thought to foster an increase in overall social satisfaction. Today's situation shows how unrealistic this assumption was. The egoistic approach of an individual leads consequently to a series of unfavorable overall changes. For instance, excessive and irrational utilization of renewable resources result at times in degradation of the surrounding environment (deforestation, desertification, pollution of water and food, reduced productivity of fisheries). Overexploitation of common resources renders their proper management difficult; uncritical faith in the self-healing power of a perfectly-functioning market and free relocation of resources has been impaired. Depletion of a resource, compounded by the impossibility of its renewal, leads to the statement that decreasing supply results in increasing prices, which lead in turn to the search for, and development of a market for, substitutes. Thus, the appearance of a barrier to growth derived from a shortage of primary resources is not considered a real threat in the long term, as the functioning of an economy in conditions of sustainable development is stabilized by a macroeconomic mechanism. The dynamic theory of resources (Barnett, Morse 1963) does not actually negate the existence of a resource barrier, but expresses it in different terms. The essence of the barrier is the acquisition of technology and costs of physical availability. Szamałek (2011) states that in the foreseeable future, the supply of mineral resources is sufficient.

1. Protection of mineral resources in the theory of sustainable development

Drawing from any of the above-mentioned paradigms, one concludes that the need to protect deposits of mineral resources is a universal and necessary challenge. Within the contemporary, neoclassical approach to managing natural resources, the assessment over time of social preferences regarding social welfare plays a major role. This assessment is directly related to determining the rate of resource utilization, on the basis of which decisions are made concerning how much of a resource should be utilized now, and how much should be left for future generations so as to maintain development in the present while also making it available for posterity. Such thinking is at the core of the idea of sustainable development, which requires continuous improvement in managing natural resources in the context of economy, ecology, and social justice (Tilton 1996; Shields 1998; Wellmer, Becker-Platen 2002).

Development, depending on the fulfillment of several important postulates, is referred to as enduring when (Fiedor 2002):

1) there is no decrease in any element of the vector of social and economic goals connected with the process of economic development,
2) net benefits of economic development are maximized, while the utility and quality of natural resources is maintained over the long term,
3) consumption of material goods and services is simultaneously limited to a level acceptable from an ecological point of view – particularly regarding the need to maintain proper environmental quality for future generations – and available for everyone (intergenerational justice).

From rules 2 and 3 concerning the stability of natural capital resources, we can derive two general principles of resource management (Camus 2002; Fiedor 2002; Wellmer, Becker-Platen 2002):

— the rate of exploitation of renewable resources must not exceed their rate of regeneration (renewal),
— the volume of waste (pollution) transferred to the environment must not exceed the environment's capacity to assimilate it.

It is hard to apply the first management goal to mineral resources. Intergenerational justice would be maintained only if the present generation refrained completely from using these resources. This would result in a decreased level of social welfare. It is hard to imagine, much less accept, such a state of affairs. Hence, different theoretical ways of escaping from such a trap have been proposed. The current utilization of non-renewable resources will not violate the welfare of future generations if (Fiedor 2002; Wellmer and Becker-Platen 2002):

1) ecological functions of the environment connected with non-renewable resources are not necessary for future generations;
2) these functions are replaced by other factors;
3) utilization of non-renewable resources will not exceed volumes which can be replaced by equivalent renewable resources or by obtaining higher efficiency in the utilization of renewable or non-renewable resources;
4) losses incurred by future generations (from the point of view of their welfare) as a result of current utilization of non-renewable resources are appropriately pre-compensated by the present generation.

The first two provisions can be honored in a situation in which technological progress allows for a continuous decrease in the consumption of environmental resources, or even for a decision to refrain from using some of them. Technological progress also allows for balancing development restraints caused by the depletion of mineral resources, and can contribute to maintaining the stability of natural capital while fulfilling postulate 3 – for instance, by obtaining energy from renewable (non-conventional) resources, such as wind, water, the sun, ocean tides, or geothermal energy, instead of primal energy from useful minerals. Non-conventional resources are practically inexhaustible. The problems here, however, are the parameters of such energy and the costs of its production. As well, an increase in the volume and availability of recycled materials and metals recovered from lower-grade ores meets the requirements of postulate 3. Recycling of wastes enables the fulfillment of two key postulates simultaneously: improvement in the marginal productivity of exhaustible resources and almost total assimilation of negative external effects, represented by accumulated wastes (Vita 2006).

Shields (1998), citing the dilemmas of the limited endurance of mineral resource bases and the need to protect them, calls attention to terminating the demand for exhaustible resources. At some point in time, depletion of deposits of useful mineral resources will outstrip their replacement resulting from new discoveries. Moreover, an increase in the prices of energy and resources, stemming from the decreasing supply, is particularly unfavorable for developing countries dependent on imports of these goods. The inability to react flexibly to price changes, rather than increasing the general welfare, will weaken the non-mining branches of the economy. From an environmental perspective, the further consumption of resources at the current level may disturb the functioning of ecosystems in various ways. In such a scenario, obtaining energy and useful minerals damages the environment irrespective of the endurance of their supply. The impact of the mining industry on the environment is in accord with the principle of endurance only as long as some "appropriate" part of the income obtained from mining activity is invested in human beings, their material and environmental capital.

It is obvious that the current consumption of non-renewable resources may lead to a decline in the well-being of future generations. A total, or more likely a partial, compensation of this loss can be provided by technical progress and substitution of a given resource (natural capital) with anthropogenic capital. The future availability of a resource is often referred to as the "reserves lifetime" or the "life index," defined as the recognized resource base (R) divided by annual consumption (C). In practice, this statistical measure of sufficiency (R/C) does not perform very well as a measure of the future availability of the resource. In the case of mineral resources, the R/C coefficient is compromised by many factors. It depends on types of deposits, costs of exploitation, prices of raw-mineral materials, the level of recognition of the resource base, the level of technological development, and many other factors (Wellmer, Becker-Platen 2002). More appropriate, although also more difficult, is the application of dynamic sufficiency ratios, including consumption changes over time function. Fig. 1 shows examples of statistical reserves' lifetime ratios for a few useful minerals.

Each of the raw material groups is influenced to a great extent by individual factors which deflect the course of the relevant statistic's sufficiency ratio. Hence, despite a fivefold increase in mining production of zinc and more than doubled production of lead in the years 1950-2008, the R/C ratio remains relatively stable, ranging usually between 20 and 30 years. In recent years, a stronger decrease of the coefficient for zinc can be observed. A similar regularity can be observed in the case of crude oil, for which the R/C coefficient since 1960 has never fallen below 30 years, despite the tenfold increase in production of this resource. It has been predicted that between 2010 and 2020, the maximum production peak will be reached, and only after that period can a change in the coefficient of statistical sufficiency

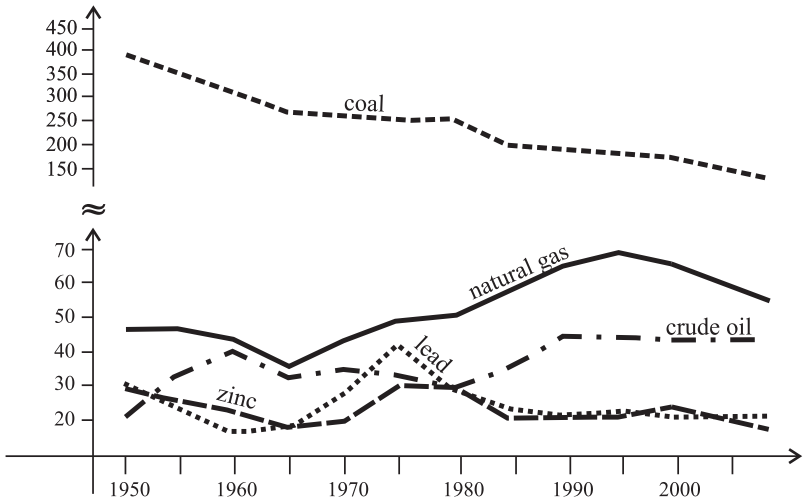

Fig. 1. Evolution of (*R*/*C*) ratio for selected useful minerals (by Wellmer and Becker-Platen 2002, updated)

Rys. 1. Ewolucja wskaźnika trwałości zasobów wybranych kopalin mineralnych

be expected (Hiller 1999). The gas market, much younger than the crude oil market, has recently reached a significant equilibrium at the level of 50–60 years. The very high *R*/*C* coefficient for coal continues to decrease; however, the sufficiency of resources of this mineral is estimated at significantly higher than 100 years.

2. Hotelling's rule and its modifications – issue outline

Resources of useful minerals, as already mentioned, are usually regarded as finite and non-renewable. In relation to a defined deposit, this means that it possesses quantity-limited reserves which cannot be substituted, and that consumption of this resource today means that its volume will decrease in the future. Analysis of mineral resource management requires a dynamic approach, because the distribution of the exploitation rate over time is important. It is possible to intensify current exploitation at the expense of the future, or to refrain from exploitation for the sake of future benefits. The factor determining optimization of the scope of utilization of a non-renewable resource is the limited nature of the inter-period sum of benefits which can be obtained [from that resource/from that utilization]. The market value of a mineral deposit draws, ultimately, from the prospect of its extraction and the pursuant sale of the mineral raw material (Solow 1974). In mining practice, this is usually connected with technical-organizational factors determining the lifetime of a mine and its economics. These factors include systems and methods of extraction, the type of technology for mineral processing, extraction rate, selective extraction of parts of deposits meeting the cutoff criteria, etc. (Camus 2002). These factors play an important role in the analysis because a unit of resource exploited today weakens the resource base and means that the availability

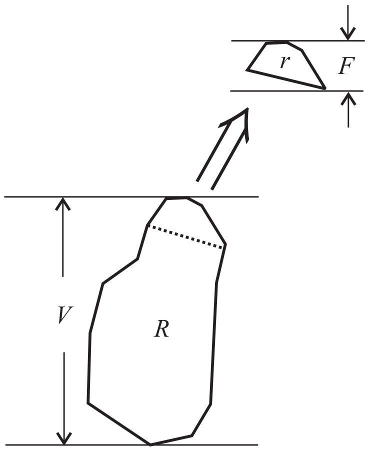

Fig. 2. Resources and their present value (by Camus 2002)

Rys. 2. Zasoby i ich wartość zaktualizowana

of the resource will be decreased by an equivalent unit tomorrow. The volume of resources remaining in the deposit changes over the entire cycle of extraction (Fig. 2).

The value F describes the cash flow coming from the fraction r, subtracted from total resources R. For the specified structure of costs, which are dependent on current market conditions, cash flow depends on the applied performance strategy. This strategy covers not only the current cash flow C, but also includes the present net value V for time t needed for obtaining resource r. This in turn refers to a point on the time scale at which the rest of the resource can be exploited. Because of this time dependence, cash flow C cannot be optimized separately from the rest of the resource remaining in the deposit (Lane 1988; Camus 2002).

Pioneer work in solving optimization problems defined in this way was undertaken by Gray (1914) and Hotelling (1931). Hotelling's rule provides a theoretical basis for determining the prices of non-renewable resources. Its essence is identifying the quantity of the resource for allocation to maximize the benefit of its consumption as a function of time. If the quantity of a resource is fixed, its current consumption is connected with a loss of the possible use of the resource in the future, which is then referred to as the user cost or royalty. In practical terms, a royalty is often identified with an exploitation fee, reflecting the scarcity of the resource, and must be taken into account when planning exploitation of the resource. A royalty in that approach is one of the most important economic tools used by the state in managing the process of minerals extraction. A detailed study of its effectiveness in the rationalization of mineral deposits management in Poland is delivered by Szamałek (2001).

The basis for solving Hotelling's model is a mode of allocating the specified value of a resource at various moments in time which would maximize its utility, i.e. the benefit derived from consumption of the resource. Moreover, Hotelling's model assumes the principle of decreasing marginal utility in resource consumption, meaning that each increase in the subsequent consumption of the resource per unit yields lower and lower levels of utility. On the other hand, the marginal costs of extraction (an increase in the mining plant's costs due to the extraction of the following unit of a resource) remain stable. The effectiveness of exploitation will be reached when the marginal utility (the maximum sum that consumers or enterprises are ready to pay for consuming the additional unit of the resource) becomes higher than the marginal costs by the value of the royalty. The royalty reflects here the value of an unexploited marginal unit of a useful mineral, assuming the possibility of its future consumption. The concept of royalties is exemplified by Fig. 3.

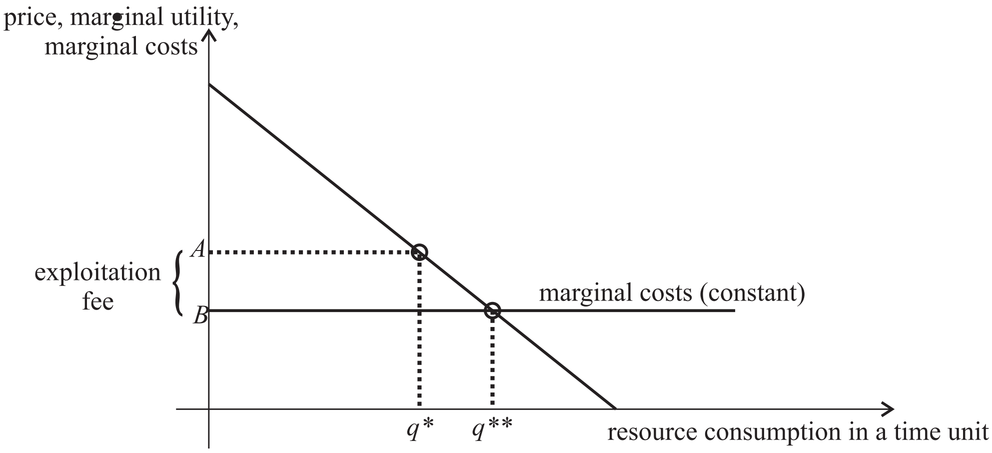

Fig. 3. Forming of the royalty over time (by Jakubczyk 2002)

Rys. 3. Kształtowanie się opłat eksploatacyjnych w czasie

For renewable resources, the production optimum would be localized at point q^{**}, where marginal utility equals marginal cost. The cost for non-renewable resources moves the optimal level of exploitation and consumption to q^*. The royalty is then "$A - B$". In other words, the lowest price at which the mining producer would agree to sell the raw material in the specified period equals marginal cost (MC). If price P is binding in the market at the specified time, then royalty D is the difference between this price and the marginal cost ($D = P - MC$). Such a solution fulfills Hotelling's static model. In the dynamic approach, changes in royalty over time are considered. The sum of such royalties over n-periods of time, until depletion of the resource, discounted to the current moment, becomes the object of maximization for the mining entrepreneur. In balanced conditions, the producer has no motivation either to increase or decrease production. It should be noted that the entrepreneur transforms (by exploitation and sale) the value of useful mineral into money, and with the passage of time, the value of the resource can grow as its volume decreases. On the other hand, money invested elsewhere also yields certain benefits. At each moment, the user considers whether it is more profitable to leave the resource for the future, expecting a relative increase in the royalty $\left(\frac{dR_t}{dt}:R_t\right)$, or whether it should be converted into money which can be invested, expecting a return expressed by the current discount rate i. Here, three scenarios are possible (Żylicz 2004):

1. $\left(\frac{dR_t}{dt}:R_t\right) > i$ – the mining user, expecting that the royalty increase will be higher than the current discount rate, decides not to increase (or even to limit) mining production,
2. $\left(\frac{dR_t}{dt}:R_t\right) < i$ – the mining user, expecting that the royalty increase will not be higher than the current discount rate, decides to increase production and sells as much of the resource as possible,
3. $\left(\frac{dR_t}{dt}:R_t\right) = i$ – the mining user, with royalty growth equal to the current discount rate, has no incentive to change the current volume of production. It is immaterial for him whether he realizes the gain today and makes interest i on the gained money, or whether he exploits the resource in the future. The discounted net gain value remains the same in all periods.

Scenario 3 is again a representation of Hotelling's rule. Royalties shall then grow exponentially, at a speed determined by interest rate i, which is the measure of the cost of lost opportunities. This means that net prices (decreased by the marginal cost of exploitation) need to grow at the same rate. It also derives from the rule that royalty growth results in decreased demand and thus decreased consumption of the resource over time. The higher the discount rate, the greater the rate of decreased consumption over time. The threat of wasteful exploitation or even of over-exploitation is minimized, also in the private ownership of mineral deposits, since the decreasing marginal utility (Fig. 3) renders exceeding production at q^* level unprofitable (Jakubczyk 2002). Beyond this point, the consumers' inclination to pay is lower than marginal costs plus royalty. The curve of marginal utility equals the curve of demand for the raw material (useful mineral). The royalty reflects here two values:

— marginal net gain of the mining entrepreneur,
— marginal net benefit of the society.

Because these categories overlap, maximization of individual gains for mining plants is equal to the socially optimal policy of resource consumption. The condition for such conformity is the exponential increase of the royalty over time at a speed equal to that of the discount rate. The royalty in Hotelling's model is thus a reflection of the discount rate.

Hotelling's model proves correct when a single resource user decides on its exploitation. Based on Tietenberg's model (1996), a simple modification of a two-period Fisher's example (1981), optimization of resource utilization is as follows. A mining plant (gravel pit) conducts gravel extraction. Resources projected for extraction over a 12-month period total 120,000 tons of useful material. The fixed marginal cost of production equals 15 Polish Zloty (zl)/ton, and the demand function is described by the equation $P = 63 - 0.4 \cdot q$. In this expression, P represents the price of gravel and q the half-year consumption (in thousands of tons) to date. It is also known that total costs are proportional to the volume of production. The mining plant is to decide on production tonnage in two, half-year periods (y_0 and y_1) in which it intends to optimize the benefit value. The broad production capacities of the mine allow it to flexibly adjust its own mining volume to market conditions. The profit of the gravel pit in a single period is the difference between the price (marginal utility) which the gravel buyer is able to pay and the cost of its production. In the calculation, the discount rate was fixed at hypothetical annual level i = 10%.

The gain of the plant in the first period (y_0) is described by the following integral:

$$\int_0^{q_0} (63-0.4q)dq - \int_0^{q_0} 15dy = \int_0^{q_0} [(63-0.4q)-15]dq$$

while in the second period (y_1):

$$\int_0^{q_1} \frac{[(63-0.4q)-15]dq}{1+0.1}$$

The limits of integrals q_0 and q_1 refer to extraction volumes in subsequent periods. When maximizing the gain value, taking into consideration discounting in period y_1, the objective function can be stated as follows:

$$F = \max(q_1, q_2)\int_0^{q_0} [(63-0.4q)-15]dq + \int_0^{q_1} \frac{[(63-0.4q)-15]dq}{1+0.1}$$

Using the method of Lagrange's multipliers and further differentiating the objective function against variables q_0, q_1, λ , the obtained partial derivatives are equal to zero:

$$\begin{cases} (63-0.4q_0)-15-\lambda=0 \\ \dfrac{(63-0.4q_1)-15}{1.1}-\lambda=0 \\ q_0+q_1-120=0 \end{cases}$$

The solutions of this system of equations are, approximately, the following values: q_0 = 62,600, q_1 = 57,400, λ = 22,963. Prices of gravel obtained by the pit will then equal 37.96 zl/t in period y_0 and 40.04 zl/t in period y_1. The royalty, measured as the difference between the price and the marginal cost, comes out to 22.96 zl in period y_0, while in period y_1 it equals 25.04 zl.

In general, if the demand function is expressed by the general equation , where a and b are constants, while q_t represents the consumption of the resource over time, and the total cost $TC = k \cdot q_t$, where k is the marginal cost of exploitation, then the optimization is done according to the formula (Tietenberg 1996):

$$\frac{a - bq_t - k}{(1+r)^{i-1}} - \lambda = 0 \tag{1}$$

where: i = 1, 2, …, n (periods assumed within the scope of the optimization time horizon) with the restriction:

$$\sum_{t=1}^{n} q_t - Q = 0 \tag{2}$$

where Q stands for the total available volume of the resource.

The two-period model can be enlarged by any number (t) of periods. It is known that:

$$(P_1 - k) = (P_0 - k) \cdot (1+i) \tag{3}$$

hence:

$$P_1 = (P_0 - k) \cdot (1+i) + k \tag{4}$$

so for t periods, the price equation for period t looks like this:

$$P_t = (P - k) \cdot (1+i)^t + k \tag{5}$$

The above formula is an example of Hotelling's rule, and it means that with an increase of t periods the price moves further from the marginal exploitation cost, growing at a rate dependent on the assumed discount rate. An interesting question is: where are the limits? Key roles are evidently played here by the prices of substitutes and the concepts of backstop technologies based upon them, which state that if depletion of a non-renewable resource takes place, then the market mechanism always leads to two interdependent results: a progressive decrease in its consumption and the appearance of a technology or resource able to effectively replace the scarce resource in its present applications (e.g. power production). Thus, the criterion of intergenerational justice is fulfilled in relation to non-renewable resources. Although substitution is possible in many applications of mineral resources, its role in many other areas is limited. The substitutes for most raw materials (excepting mineral fuels) are usually found within other raw material groups, and are not always characterized by longer time sufficiency. Such substitutions can only partially solve the problem of protection and optimal utilization of limited mineral resources.

Hotelling's model has been repeatedly referenced, analyzed, and discussed in scientific publications. Many years later the hotelling's idea is still valid in relation to non-renewable resources (Devarajan, Fisher 1981). In many studies, this model has met with both criticism and praise. The comments below represent only a few of these citations.

Pindyck (1978), omitting a number of factors (effect of common access, market structure other than monopoly and perfect competition, government control, uncertainty) indicated that for an initially small reserve endowment, the price profile would be U-shaped rather than steadily increasing according to Hotelling's rule. Hotelling's rule works in the later stages of resource usage or throughout if the initial reserve endowment is large. However, geological discoveries will reduce the rate of price increase. The issue of uncertainty in relation to the exploration process in Hotelling's model is investigated in detail by Desmukh and Pliska (1980). The dynamics of scarcity rent under competitive conditions and in the absence of exploration activities has been examined in the paper by Farzin (1992). Hotelling's rule, not taking into account the risk, specifies that equilibrium rates of return on nonrenewable resource assets and on alternative assets will be equalized. Young and Ryan (1996), based on various resource industries (lead, zinc, copper, silver), report a preliminary empirical attempt to incorporate risk explicitly into an industry-level Hotelling model of resource extraction. Krautkraemer (1998) points out the fact that finite resource availability creates a Hotelling's rule. However, other factors – explorations, capital investment, heterogeneous quality of ore – are also important for the economics of non-renewable resources These factors explain the failure of Hotelling's rule in many aspects within the context of repeatedly observed dynamic prices behavior and the *in situ* value of a mineral deposit. These other factors can affect price and depletion paths in a number of ways. Black and LaFrance (1998) tested Hotelling's rule on the realities of the domestic supply of oil production in the U.S., concluding that the producers, in addition to the development of new drilling, are likely to change both the current production level and the length of the production horizon of existing wells in response to price changes. Brazee and Cloutier (2006) formalized ideas presented by Gray (1914) in a dynamic model exploring the distinctions between the concepts expounded by Gray and Hotelling. A result of that investigation was a statement that Hotelling's r-percent rule could be shown as a special case of Gray's rule under Gray's assumptions of fixed costs and assumed by the authors' entry costs. Additional results show that by considering spatially identifiable heterogeneous deposits – fixed costs and entry costs – in general Hotelling's r-percent rule is not a sufficient condition for company/corporate-level decision making and that production companies' extraction behavior cannot be linearly aggregated to describe industry behavior. Gerlagh and Liski (2011), analyzing the producer/ /consumer oil dependence, prove that the rising consumers' cost burden as the effect of resource depletion results in a producers' market power reduction. The consequence is the need to increase supply by the producer to postpone the buyer's action. That strategic dependence reverses the basic implications of Hotelling's model. In Polish publications, Hotelling's theory in relation to the valuation of mineral deposits and mineral resources management has been invoked, among others, by Uberman (2002, 2009) and Pera (2010).

3. N-person Prisoner's Dilemma

The reports of the Club of Rome turned the world's attention to the hazard of global ecologic catastrophe, in which the early depletion of resources of all important, useful minerals was foreseen (Meadows et al. 1972). That point of view necessitated a search for alternative economic models describing the level of exploitation and depletion of natural resources. The model of the N-person Prisoner's Dilemma (NPD) soon became popular among economists, and its initial applications were published in the early 1970s. Hardin (1968) suggested that the structure of the NPD model was applicable to many of the most important problems of the late twentieth century – depletion of natural resources, environmental pollution, demographic booms, and political problems. He also introduced the well-known concept of the "tragedy of the commons," where this metaphor – a pasture devastated by the common grazing of cattle belonging to six farmers – stood for the problems of resources which are, firstly, attractive; secondly, held in common; and thirdly, depleted or destroyed if overused.

In the classical problem of the prisoner's dilemma, as formulated by Tucker in 1950, two men are accused of violating the law together. They are kept by the police in two separate cells and each is given the following proposal:

1) if one of them confesses, and the other does not, then the first one will be given one unit of a given utility, while the other will be punished by two units,
2) if they both confess, each will be punished by one unit,
3) if neither of them confesses, they will be both freed from charges.

The table of payoffs of this symmetric, two-person game is presented by the matrix below (6).

player 2 (6)

		β_1 (to confess)	β_2 (not to confess)
player 1	α_1 (to confess)	–1, –1	1, –2
	α_2 (not to confess)	–2, 1	0, 0

The game here is a conflict situation with two players, each with a range of possible moves which determine the way he plays the game. The result is determined by a combination of strategies chosen by the players, and each result is reflected by fixed payoffs. It is obvious for each of the prisoners that the strategy "to confess" dominates (the dominant strategy in games theory means that some strategies are better than others) over the strategy "not to confess." Suitable players' payoffs are larger. For example strategy α_1 of player 1 always offers more "$-1 > -2$" and "$1 > 0$" regardless of the player 2 choice. A strategy pair (to confess, to confess) fulfills Nash's equilibrium (Nash 1950). This balance is often ineffective in Pareto's sense; it is dominated by the strategy profile (not to confess, not to confess). That profile provides (0, 0) payoffs which are better than (–1, –1). Both of the accused would benefit more if they followed this profile – they would be freed from charges. Such a solution would require some cooperation and confidence between the players, or at least the possibility of mutual communication (which is, however, excluded by the rules of the game).

The prisoner's dilemma is quite often applied when presenting certain aspects of economic reality. It is particularly useful in situations with more than two participants. In a conjuncture modeled this way, it turns out that cooperation can be risky and, moreover, ineffective. In relation to resource utilization, the actual benefit applies to an entity (an individual, group of people, organization, etc.) only when other users of the resource also refrain from its exploitation (however, it turns out that moderation of a single entity is not always necessary). It means that individual decisions to refrain from utilizing a resource, when others decide otherwise, is in vain and the resource will not be protected anyway. Acting for one's own benefit only worsens the situation of all users of the resource.

The N-person Prisoner's Dilemma is a game in which each of *n* players has two strategies (α_1, α_2) at his disposal, such that:

— for each player, α_2 is the dominant strategy,

— if all participants play α_2, they will earn worse payoffs than if they played α_1.

Strategies α_1 are usually named cooperation strategies, while α_2 betrayal strategies. Players facing the prisoners' dilemma are strongly motivated to forge an agreement (Dixit, Nalebuff 2009). Betrayal is the dominating strategy for each player and, hence, the better choice, regardless of how many other participants of the game decide to cooperate.

For an example of NPD, the same kind of mineral resource as in Tietenberg's model was used. Several deposits of a mineral aggregate have been discovered in a certain place. Six different mining users have decided to develop them. Very similar deposit parameters enable the users to obtain sorted gravel of almost identical quality and identical *Ex-Works* price. Assuming that each of the mining plants (gravel pits) can meet the demand of 10,000 tons of useful mineral/month, each ton of sorted gravel sold yields 39 zl. Doubling production in any plant will result in a decrease in price of 4 zl/ton. Besides the price decrease, the higher level of resource exploitation results in a shorter lifetime for the mining plant and an eventual shortage of the aggregate in the local market.

The presented situation is a six-person game, where every player has two strategies at his disposal. The first gravel pit provides for extraction of 10,000 tons, while the second 20,000 tons. Higher production output can result in a price decrease. To be precise, it should be mentioned that the players actually have three strategies – besides the strategies covering extraction of 10,000 or 20,000 – the third being to abort extraction. The payoffs to the players would then equal 0 units, and the resource base would remain untouched. Such a scenario, while meeting the requirement of resource protection, would not guarantee economic development of the region; thus, this strategy was not considered during further research.

Presentation of the game in the normal form was simplified, taking into account the fact that payoff for any of the players depends on their own output and the total production of other players (7). The columns stand for the aggregate moves of other players, and the payoffs are given in thousands of zl.

number of participating gravel pits α_1 (7)

		0	1	2	3	4	5
a single pit	α_1 (cooperation) = = 10,000 t	190	230	270	310	350	390
	α_2 (betrayal) = = 20,000 t	300	380	460	540	620	700

According to what has been said about games of the "prisoner's dilemma" type, strategy α_2 strictly dominates α_1. Extraction of the mineral resource in the volume of 20,000 t/month is the best strategy for each gravel pit, regardless of the moves of the other gravel suppliers. Application of this strategy is an intuitively rational choice for each mining plant. However, through such behavior, each of them will gain a payoff of 300,000 zl, whereas at a production level of 10,000 tons, the payoffs would be higher, in the sum of 390,000 zl. All the components of the vector of payoffs (390, 390, 390, 390, 390, 390) are higher than those of vector (300, 300, 300, 300, 300, 300); thus, this is a Pareto optimal vector. Additional configurations of strategies for which payoffs are optimal in Pareto's sense appear in the strategy. These are the following sets:

— (α_2, α_1, α_1, α_1, α_1, α_1) with payoffs (700, 350, 350, 350, 350, 350),

— (α_2, α_2, α_1, α_1, α_1, α_1) with payoffs (620, 620, 310, 310, 310, 310).

An eventual coalition, if it were to take advantage of the fact that each of its members played α_1, would have to include at least 4 gravel pits. Mining plants opting out of the coalition would then get 620,000 zl. Each pit would surely support the establishment of such a coalition, but it would also do its best to stay out of it as a "free rider."

The payoffs vector (390, 390, 390, 390, 390, 390) yields total incomes for all pits in the amount of 2,340,000 zl and a total supply of 60,000 tons of sorted gravel. Doubling the production by a growing number of plants will generate total incomes on the level:

— 2,450,000 zl from a total supply of 70,000 tons of gravel,
— 2,480,000 zl from a total supply of 80,000 tons of gravel,
— 2,430,000 zl from a total supply of 90,000 tons of gravel,
— 2,300,000 zl from a total supply of 100,000 tons of gravel,
— 2,090,000 zl from a total supply of 110,000 tons of gravel,
— 1,800,000 zl from a total supply of 120,000 tons of gravel.

Changes in the total income in relation to production volume are reflected in Fig. 4. The optimal total value of incomes is yielded by a gravel supply of approximately 80,000 tons, point C (precisely, 78,750), which means production of 20,000 tons of gravel in two pits and 10,000 tons in each of the others. All configurations of strategies representing total production volume from the bracket [60,000–96,923] with proper payoff vectors are Pareto optimal.

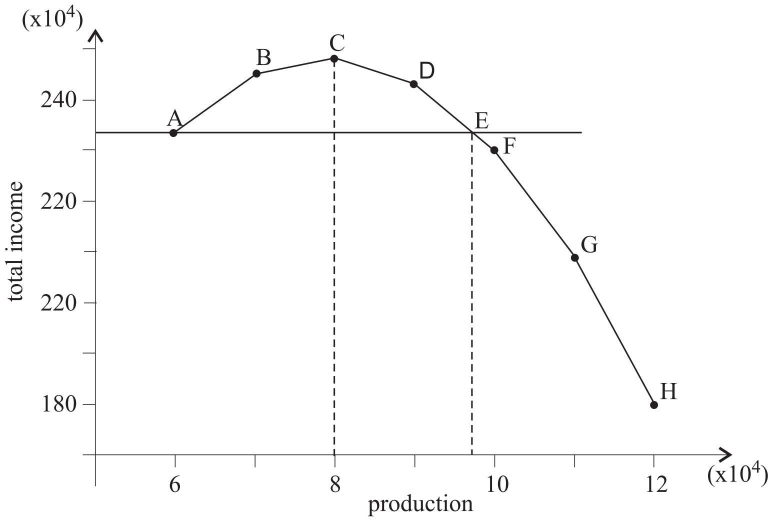

Fig. 4. Total income of gravel pits depending on the level of production

Rys. 4. Łączny przychód żwirowni w zależności od poziomu produkcji

At the available gravel supply of 96,923 tons (point E), the total income of mining plants would reach a level identical to that earned by production of 10,000 tons each. Gravel pits would then be able to produce, for example, 16,154 tons of gravel per month each. The broken line in both sections AC and CE is equally beneficial for deposit users; however, the postulate of resource protection would be fulfilled in the AC section. Decreasing extraction by each plant would be advantageous for each of them. Unfortunately, none of the gravel pits has any incentive to do so. On the contrary, according to the fixed strategies of other players, it is beneficial to increase production – if only one plant does so, it will gain while others lose. Individual interest, as in many real economic situations, is stronger here than the best interests of the whole.

Conclusions

The appropriately early rationalization of the utilization of non-renewable natural resources may enable prolongation of their usage and, hence, mitigate the severity of a possible raw material crisis for future generations. However, there is still no unequivocal answer to the frequently-asked question concerning how contemporary societies can prevent such a potential raw material crisis in the future, or if this aim is even attainable. Numerous discoveries of new deposits, in particular since World War II, have alleviated distressing signs of resource depletion. They have even led to the statement that the problem of resource depletion was actually unimportant, as the decrease of resources was constantly being compensated thanks to new discoveries (Nieć 2008). Moreover, technological progress and substitution available in many resource areas resulted in a slowed rate of exploitation of resource bases of useful minerals. From the economic point of view, contrary to the prognoses of the Club of Rome, no threatening signs for the supply of useful minerals have been observed (Radetzki 2002). The decrease in the supply of raw materials results from the growing cost of their exploitation, caused mostly by technological barriers in the exploitation of low-grade deposits. In recent times, a problem of a different kind – the availability of deposits – has arisen. Exploiting resources in highly populated, urbanized, or environmentally-protected areas has become complicated and sometimes even impossible. Protection of undeveloped but proven mineral reserves is required here. Proper land use planning is a fundamental tool protecting limited mineral resources in this conception. For some important groups of raw materials (e.g. deposits of crude oil and natural gas), political factors play a part as well.

The awareness of the necessity of non-renewable resource protection encounters barriers in its translation into action. This is strongly highlighted by the N-person Prisoner's Dilemma, where each player would support protection-oriented activity, but only without making a personal commitment. Under conditions of non-cooperation, the "invisible hand" of the market does not work. Also, Hotelling's theory, as well as its later modifications, indicates that the issues of resource protection depend on the assumed discount rate. Thus, it is economic calculation, not the convictions of the user, which decides whether a resource will be protected. Here, optimal resource management guarantees the maximum stable income by providing for royalties from resources belonging, in an economic sense, to future generations.

A way to reach an agreement in games of the "prisoners' dilemma" type is betrayal avoiding, thus not-applying dominating strategies. Some incentive must constitute the motivation for these proceedings, e.g. an appropriate reward, or a heavy penalty corresponding with the deception. Policies protecting the sustainable use of mineral resources, preventing the exaggerated exploitation and overly-rapid exhaustion are not simple and should meet numerous conditions. Dixit and Nalebuf (2009) distinguish here:

- clear rules related to the identification of group members taking part in a game,
- clear rules determining permitted and forbidden actions,
- a transparent system of penalties in case of breaking of the law,
- developing a good system for detecting betrayal.

Unfortunately, even in spite of a well-functioning system, avoiding the prisoners' dilemma is unusually difficult, and monitoring and sanctions are not reducing the temptation of betrayal to nought. It seems that administrative systems intended to avoid the "tragedy of the commons" will continue to cope with the problem. Szamałek (2011) points to the need for cooperation in the protection of mineral deposits by both the state and the mining industry. The method of enforcement could be exploitation fees and/or other extra charges for economic usage of environmental resources, changing the structure of payoffs, and should force behavior where the excessive use of a mineral resource stops being individually profitable. Admittedly, that interventionism is not solving the dilemma, but by changing the game rules it is extorting a change of behavior and actions. The more important issue, however, would appear to be the recognition of mining as a crucial field for maintaining the sustainable and stable welfare of society.

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DYLEMATY UŻYTKOWANIA ZASOBÓW KOPALIN MINERALNYCH W WYBRANYCH TEORIACH EKONOMICZNYCH

Słowa kluczowe

Zasoby mineralne, reguła Hotellinga, model Tietenberga, *n*-osobowy dylemat więźnia

Streszczenie

Rozwój cywilizacji człowieka napędza popyt na różnego rodzaju zasoby naturalne. Obecnie obejmuje on nie tylko kopaliny mineralne, glebę, wodę, powietrze, florę czy faunę, lecz także siły przyrody i inne walory środowiska, determinujące jakość życia człowieka, takie jak: przestrzeń geograficzna, krajobraz, mikroklimat i in. Spomiędzy tak wielu odmiennych kategorii zasobów naturalnych okazuje się, że bogactwa mineralne, w zdecydowanej większości nieodnawialne, mają często decydujący wpływ na poziomu dobrobytu. W teorii eksploatacji zasobów naturalnych wypracowano dotychchczas szereg różnych modeli, które – najczęściej w sposób dynamiczny (uwzględniając czynnik czasu) – maksymalizują wielkość społecznego dobrobytu implikowanego korzystaniem z zasobu.

W artykule, przypominając wybrane, ugruntowane teorie ekonomiczne, poruszono problematykę użytkowania i ochrony nieodnawialnych zasobów kopalin mineralnych na etapie ich gospodarczego użytkowania. Wykorzystując teorię rozwoju trwałego, model Hotellinga i jego późniejsze modyfikacje uwypuklono trudności realizacji polityki w zakresie ich ochrony. Przybliżono spojrzenia na koncepcję użytkowania zasobów mineralnych w świetle N-osobowego dylematu więźnia. Rozważania zobrazowano prostymi przykładami, realizując je przy założeniu braku doskonałego, nieograniczonego substytutu.

DILEMMAS OF MINERAL RESOURCES USE IN SELECTED ECONOMIC THEORIES

Key words

Mineral resources, Hotelling's rule, Tietenbeg's model, *N*-person Prisoner's Dilemma

Abstract

The development of human civilization ignites a demand for various natural resources. Nowadays, these resources include not only useful minerals, soil, water, air, flora, or fauna, but also natural forces and other environmental assets determining the quality of human life, such as geographic space, landscapes, and microclimates. Among so many categories of natural resources, minerals – which are for the most part non-renewable – often constitute a deciding influence on the level of human well-being. Within the study of the utilization of natural resources, a series of models have been developed which are aimed – mostly in a dynamic mode – at maximizing the level of social well-being determined by the consumption of specific resources.

The paper discusses, while recalling selected, established economic theories, the problem of the use and protection of non-renewable mineral resources at the stage of their economic exploitation. The author examines, based on the theory of sustainable development, Hotelling's model and its later modifications of the difficulties in implementing a resource protection policy. The paper approximates a new approach to the concept of mineral resources use in light of the *N*-person Prisoner's Dilemma. The conclusions were illustrated by simplified cases, conducted with the assumption of an absence of perfect unlimited substitutes.