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Environmental Risks Related to the Recovery and Recycling Processes of Waste Electrical and Electronic Equipment (WEEE)

Ryzyka ekologiczne związane z procesami odzysku i recyklingu zużytego sprzętu elektrycznego i elektronicznego (ZSEE)

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Abstract
The idea of sustainable development imposes waste management tasks that can be solved only using a systemic approach. It requires that municipal waste management is carried out in a technically correct manner, is economically efficient, socially acceptable, with no negative effect to the natural environment and takes into account economy of all waste streams, including electrical and electronic waste (E-waste). A relentless pursuit of comfort, quality of life as well as rapid technological changes result in products of a shorter life cycle, which quickly become just electro scraps. There are many of them with a different composition. E- waste may include e.g. toxic metals, which if released to the environment may pose a threat to human life and health. At the same time, recovery of valuable secondary raw materials complies perfectly with implementation of the principles of sustainable development. In recent decades, the risk assessment for the natural environment and decision-making strategies have become a target of intense and complex research undertaken also in the waste management area. The main objective of risk assessment is providing a rational basis to make unbiased decisions about the system. The article attempts to identify and assess risks of an environmental impact resulting from negligence or operational disturbances in a system of recovery and recycling of electrical and electronic waste.

Key words: electrical and electronic waste, WEEE, risk analysis, waste management, e-waste, environmental pollution

Streszczenie
Filozofia zrównoważonego rozwoju narzuca gospodarce odpadami zadania, które mogą być rozwiązane tylko w przypadku traktowania jej w sposób systemowy. Ujęcie systemowe wymaga zapewnienia aby gospodarka odpadami komunalnymi była rozwiązana w sposób technicznie poprawny, ekonomicznie efektywny, społecznie akceptowany i nie oddziaływujący negatywnie na środowisko przyrodnicze oraz uwzględniała gospodarkę wszelkimi strumieniami odpadów, w tym również zużytym sprzętem elektrycznym i elektronicznym. Nieustające dążenie do komfortu, poprawy jakości życia oraz gwałtowny postęp technologiczny, powodują powstawanie produktów o coraz krótszym cyklu życia, które stają się właśnie elektrozłomem. Poza faktem, że jest ich dużo istotne znaczenie ma również ich skład. Elementy elektrozłomu zawierają m.in. metale toksyczne, których uwolnienie do środowiska może wpłynąć na jego skażenie, co w rezultacie będzie stanowić zagrożenie dla zdrowia i życia ludzi. Równocześnie odzysk tych cennych surowców wtórnych wpisuje się w realizację zasad zrównoważonego rozwoju. Ocena ryzyka dla środowiska naturalnego i strategii podejmowania decyzji w ciągu ostatnich kilkudziesięciu lat stają się celem intensywnych i złożonych badań, podejmowanych również w zakresie gospodarowania odpadami. Zasadniczym celem oceny ryzyka jest dostarczenie racjonalnych podstaw do podejmowania wyważonych decyzji dotyczących danego systemu. W artykule podjęto próbę rozpoznania i oszacowania ryzyk oddziaływania na środowisko naturalne wynikających z zaniedbań lub nieprawidłowości funkcjonowania systemu odzysku i recyklingu odpadów elektrycznych i elektronicznych.

Słowa kluczowe: odpady elektryczne i elektroniczne, zużyty sprzęt elektryczny i elektroniczny, ZSEE, analiza ryzyka, gospodarka odpadami, elektroodpady, skażenie środowiska

1. Introduction

Waste electrical and electronic equipments (WEEE) also called e-waste or electro waste has become a quickly growing group of waste in developed countries. A permanent pursuit of comfort, quality of life as well as rapid technological changes result in products with a shorter life cycle, which quickly become just electro scraps. In the EU, approx. 8 million tons of e- waste is produced each year while about 20-50 million tons worldwide. The wastes are diverse in nature, both in terms of their quantity and composition. They contain e.g. non-ferrous and noble metals as well as rare earth elements. Their recovery, recycling and reuse provides valuable and expensive secondary raw materials and disregarding these activities would show both lack of economic awareness and care for the environment (2008/98/EC). On the other hand, toxic elements electric waste may pose a threat to people and the environment in case of their uncontrolled release into the environment (Hora, 1996; Ongondo, 2011).

The paradigm of sustainable development formulated in the report *Our Common future* and defined by the World Commission on Environment and Development, as *development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs* (Pawlowski, 2008) presents a new challenge to the e-waste economy. The growing consumerism, manufacturers that continuously push for a purchase of new equipment as well as production of less and less reliable electrical and electronic equipment result in faster depletion of natural resources, while recycling (reprocessing) the used ones. Once secondary raw materials, not properly recovered from e-waste, get into the environment, they may worsen its conditions, strengthening harmful ecological effects and generating economic losses. Therefore, an analysis of environmental risks for processes of recovery and recycling of waste electrical and electronic equipment is clearly justified; negligence in these area accompanied by an excessive consumerism may not only pose a threat to the environment but also deplete resources, which are a base for development of future generations. The article highlights the different types of risks related to e-waste and concerning the quality of the environment. It is necessary to manage these risks against the real threats.

2. Risk management

Today it has been a popular notion that no human activity, no installation nor any object is risk-free. Colloquially, risk is defined as the possibility of occurrence of a harmful (dangerous, undesirable) event causing losses (e.g. financial), damages (e.g. health, environmental) or any other negative effects. To reduce the chance of harmful scenarios and to ensure the minimization of losses it is necessary to manage risk.

A comprehensive risk management process is based on two main processes, which then comprise other sub-processes (IEC 60300-3-9, EN ISO 14121-1, EN 1050: 1999). These are:

- risk assessment which consists of risk analysis (a scope of risk or a plan of analysis, identification of threats and risk assessment) and determination of a possible risk (whether risk reduction is necessary),
- risk control, i.e. the process of making rational decisions about choosing means and methods for risk reduction and monitoring .

Identification of threats helps to recognize what bad could happen and what are the possible causes and effects of such event. The analysis should take into account events that had occurred in the past (based on a historical knowledge) and the ones that have not happened yet but are potentially possible (Iwanejko, 2005; Rak, 2005, 2008).

A risk assessment requires selection of risk measures, which have to be developed with a proper method. The classic and most commonly used measure of risk is $R = P \cdot S$, where P is a probability that a fault and some losses occur while S is a magnitude of losses. Depending on the needs also other measures can be introduced, suitable for the particular problem. These can be numbers (e.g. the average loss $R = ES$, the maximum loss $R = \max S$ or probability of occurrence of the loss $R = P$) or functions (e.g. probability that certain profits cannot be achieved), single or complex (including a number of risk factors). There are 3 main groups of the risk assessment methods. They include the following methods:

- uantitative (accurate), used when a large number of reliable data is available; the resulting R is *accurate* in the sense that it is the real value (e.g. probability P is a number between 0 and 1, losses are defined with some accuracy in monetary units); the methods include statistical and probabilistic methods as well as reliability methods,
- quality (semi-quantitative), used when a small number of unreliable data is available; the result is a relative value within a generally accepted range of values (e.g. probability is 6 on a scale of 1 to 9); these methods include e.g. matrix methods, preliminary hazard analysis PHA (Preliminary Hazard Analysis), a risk graph, FMEA (Fault Mode and Effects Analysis),
- quantitative – quality, which, depending on the available information, needs and an application mode can be considered and used as quantitative

or qualitative methods; they include e.g. methods of logic tree: the event tree method ETA (Event Tree Analysis) and the fault tree method FTA (Fault Tree Analysis).

The final risk assessment is based on the recognition of risk acceptance criteria. Development of these criteria is one of the most difficult tasks, because they play a crucial role in a decision-making process and therefore various aspects have to be considered (e.g. technical, economic, social, environmental and philosophical-ethical) that require value judgments. Risk can be:

- acceptable (RA) – or small with no need for reduction,
- tolerable (controlled) (RT) – or average; it can be accepted conditionally if costs of its reduction are too high comparing to the possible profits after risk reduction; the ALARP principle applies (As Low As is Reasonably Practicable) i.e. a risk level as low as reasonably justified. It should be noted that sometimes the maximum risk reduction may be not only too expensive but also technically unfeasible; the RT level depends on the society well-being (Rak, 2005, 2008).
- unacceptable (RN) - that is high; such risk must be reduced at all costs (system modernized or put out of operation).

The best way to reduce risk is to eliminate possible hazards and prevent occurrence of harmful events. Another method, once an event took place, is to minimize its effects (i.e. medical, technical, chemical emergency, etc.). Each way of risk reduction is associated with certain measurable costs. Therefore, the decision must always be a compromise between possible costs (investment, operational) and other residual risks. Regardless of a size of real risk, it should be monitored. Risk management process (i.e. identification of hazards, risk assessment, evaluation, possible reduction and tracking/monitoring of risk) is a continuous and cyclic process.

Risk may be considered and tested in various aspects. Its negative effects may be different (human life and health, environment, finance, etc.). Risk can be studied at a micro level (local e.g. for one community, one plant) or at a macro scale (global e.g. regions, countries). It can be associated with an event, action or an object.

3. Environmental risks associated with e- waste management

In terms of environmental risk, the following risks should be considered:

- environment pollution through careless ways of e- waste disposal: illegal waste dumps, containers for municipal waste (if not properly separated WEEE will end up at landfills or in incinerators) and unprofessional dismantling (to recover valuable raw materials, e.g. copper but without recovery or recycling of other hazardous materials); such actions release dangerous or toxic substances to air, soil or groundwater,
- need for recovery of raw materials, that had not been recovered from e- waste; in extreme cases it could violate the principles of sustainable development (too intense and unnecessary *depletion* of natural resources) and rules of closed circuit economy (Pawłowski, 2008; Bielińska at al., 2014; Generowicz, 2014),
- demand for an early closure of landfills due to a slow biomass reduction and pointless storage of bulky waste; in a long term a new landfill has to be open that may severely change the landscape,
- risk for the human health and life of people engaged in unprofessional collection, dismantling and recovery of raw materials with primitive methods and no professional equipment and premises; risk for local dwellers subjected to harmful effects of such activities (e.g. melting or burning of cables or dismantling of refrigerators).

4. Impact of harmful substances on the environment

E-waste that has not been recovered and recycled usually goes to landfills where it is mixed with other waste and not always separated at segregation units. A poor segregation *at source* may pose a risk to the natural environment and therefore for humans (Kiddee, 2013; Kowalski et al., 2015; Neri et al, 2003; Robinson, 2009; Tsydenova, 2011; Widmer, 2005; Mikosz et al., 2014). Heavy metals, which constitute electrical and electronic waste, if placed in a long term/small dose mode can harm the environment and cause chronic poisoning in humans. The hazardous stream in municipal waste includes: fluorescence lamps (mercury lamps, etc.), accumulators, batteries, paints and varnishes and used up electrical and electronic equipment. In Table 1 (Oguchi et al., 2013; Laskowski, 2004) a content of heavy metals in circuit boards of various electrical or electronic equipment is shown.

Toxic metals highlighted in the table above include toxic, noble and base metals.

Toxic metals:

Barium (Ba) – enters surface water with industrial waste or can be flushed from geological formations. It can be found in many products, which is why a lot of waste with barium passes to the environment. In 2002, the Environmental Protection Agency (US) reported that about 100 million kg of barium compounds were legally released into the air, lakes, rivers, wells and landfills. Today, public water supplies are almost everywhere contaminated with barium. An excessive exposure to this element can cause: breathing difficulties, high blood pressure, arrhyth-

Table 1. Metals in circuit boards of various used up electrical or electronic equipment (Oguchi et al., 2013)

Equipment	No	Metals in circuit boards (mg/kg)													
		Toxic metals						Metals					Precious metals		
		Ba	Be	Cd	Cr	Pb	Sb	Al.	Cu	Fe	Sn	Zn	Ag	Au	Pd
Refrigerator	1	82	-	85	27	21000	2700	16000	170000	21000	83000	17000	42	44	-
Washing machine	1	65	-	-	39	2200	150	1000	70000	95000	9100	2400	51	17	-
Air-conditioner	1	320	-	3	11	5800	310	6900	75000	20000	19000	4900	58	15	-
TV Cathode-Ray Tube	5	2400	-	12	57	14000	3200	62000	72000	34000	18000	5300	120	5	20
TV plasma display panel	2	3900	-	-	100	7100	800	38000	210000	20000	15000	12000	400	300	-
LCD TV	1	3000	-	-	-	17000	1800	63000	180000	49000	29000	200000	600	200	-
PC desktop	8	1900	1	9	270	23000	2200	18000	200000	13000	18000	2700	570	240	150
Notebook PC	2	5600	32	2	610	9800	1300	18000	190000	37000	16000	16000	1100	630	200
Video Cassette Recording	2	1200	-	9	150	20000	1300	35000	160000	38000	18000	16000	210	23	50
DVD player	3	4300	-	2	320	12000	1200	54000	220000	11000	22000	26000	710	150	20
Mobile CD player	2	8600	-	-	770	12000	1400	68000	200000	46000	50000	20000	3700	370	10
Remote player	2	19000	60	-	4000	9300	1200	27000	330000	45000	48000	11000	3400	940	550
Video game	6	5100	-	1	800	13000	2900	40000	190000	77000	26000	12000	740	230	43
Microwave	1	2000	-	-	860	17000	5800	14000	320000	400000	15000	28000	2000	-	-
Popcorn maker	1	340	-	-	530	5400	2600	20000	350000	200000	29000	39000	840	-	-
Electric pot	1	1800	-	220	850	22000	9700	40000	230000	74000	33000	30000	2500	-	-

mia, stomach irritations, muscle weakness, nerve tricks, damage of brain, liver, kidneys and heart (www.era-zdrowia.pl/). The toxicity of barium increases with its solubility. $BaSO_4$ is practically non-toxic, while $BaCl_2$, Ba $(NO_3)_2$, $BaCrO_4$, $BaCO_3$ and $Ba(CH_3COO)_2$ are highly toxic. A toxic dose of $BaCl_2$ is 0.2-0.5 g while the lethal dose is 0.7-0.9 g; a toxic dose for $BaCO_3$ is 0.6-0.9 g while the lethal dose is 1.2-2.0 g. For the remaining compounds the lethal dose is 2-4 g. Poisoning usually involves ingestion and shows symptoms of acute poisoning. The dose is determined per 1 kg of body weight (Seńczuk, 1994).

Beryllium (Be) – toxicity of beryllium compounds depends on their physical and chemical properties. Soluble beryllium compounds are more toxic than poorly soluble and insoluble ones. Highly dispersive beryllium dust produced during recovery and recycling processes is very toxic. The soluble compounds show both acute and chronic toxicity, while others produce toxic effects after a long-term exposure and cumulation (Madej, 1999).

Cadmium (Cd) – one of the most dangerous environmental poisons, it is highly toxic. It can be found in fuel oil, diesel oil, it is added to alloys, brazes, or as a pigment in production of paint, glazes, ceramic, or as an additive for plastics. It is also used in production of batteries and can be often found in electrical and electronic equipment. It can be harmful in any form and its lethal oral dose is 30-40 mg. Cadmium accumulation takes place primarily in the kidneys; accumulation above the threshold level of 0.2 mg/l g of kidney weight results in severe poisoning. Once in the environment, cadmium is generally not recoverable, it accumulates in the natural environment, enters the food chain and then with food is taken up by living organisms. Due to a good solubility cadmium salts penetrate to plants, which consume up to 70% of cadmium from soil and 30% from the air. Especially dangerous are fungi and lettuce, both cadmium reservoirs. A large supply of iron and vitamin D in the diet may prevent cadmium ab-sorption. It is extremely difficult to excrete cadmium from the body; a period of half-excretion is 20 years.

Severe poisoning with cadmium was observed in Japan, where in the 60s of the last century zinc mine polluted the Jintsu river with cadmium and water used to irrigate rice plantations was contaminated (rice and wheat intensively accumulate cadmium). Within 15-30 years over 150 people died of chronic toxicity. The disease is manifested by atrophy of bone tissue (softening and brittle-ness) and known as the Itai-Itai (ouch-ouch) disease (faculty.virginia.edu; Seńczuk, 1994).

Chromium (Cr) – chromium compounds damage a respiratory system, digestive tract and cause skin changes; they also show carcinogenic, mutagenic, embryotoxic and teratoxic effects. Toxic effects are associated with the oxidizing properties of hexavalent chromium. Formation of stable complexes with proteins and ability to precipitate proteins was considered as a mechanism of local, adverse effects of chromium on skin and mucous membranes. During acute poisoning both kidney and digestive tract may suffer. Chronic poisoning cause disorders of the respiratory system, skin changes and gastrointestinal disorders. In plants, chromium disrupts uptake of other components necessary for a proper plant growth. The excess of this element causes chlorosis, which results in a disturbed water circulation and damage of growth cones and root systems (Laskowski, 2004; Seńczuk, 1994).

Lead (Pb) – has a very wide range of applications; it is present in antyradiation screens, in covers of electric cables, in production of wires, batteries, etc. The amount of lead absorbed from the environment to a human body depends on its form, absorption pathways, human metabolic activity, sex and age. Lead in humans can cause a synthesis of hemoglobulin and anemia because it inhibits enzymes involved in hematopoiesis. In addition, it builds in bones; at certain concentrations it may impair growth, hearing and intellectual development of children. At higher doses, it is followed by weight loss, anemia, damage of vital organs and even death. The excessive amounts of cadmium adversely affect the essential life processes of plants such as: photosynthesis, cell division, nitro-gen metabolism and water management. The toxic effects include lower yield, small dark green or red leaves, occasionally with necrotic spots, and shortened roots with a lower trichomes density (Seńczuk, 1994). Mobility of lead in plants is very limited; in general more than 90% of the element is accumulated in the roots. Uptake of Pb from the soil by plant roots is small and therefore the total Pb content in the soil above 500 mg/kg is referred to as toxic to plants. (Munoz et al., 1998).

Antimony, (Sb) – antimony compounds are absorbed slowly from a digestive tract and are deposited in a liver, kidneys and thyroid gland. Trivalent antimony compounds accumulate in red blood cells while pentavalent in plasma. Symptoms of poisoning are rarely reported. The oral lethal dose for humans is 500 mg/g of body weight; the lethal concentration of antimony for mice is 100 mg/m^3 of the air. Symptoms of acute poisoning include headache, weakness, dizziness, vomiting and diarrhea. Chronic poisoning can damage heart functions and is usually associated with an occupation-al exposure. The concentration of antimony in the air is strongly related to man activity. Thus, the concentration of antimony in the air of a less polluted southern hemisphere is 0.001 ng/m^3, while at a more polluted northern hemisphere is about 0.1 ng/m^3. Concentrations in soils are in range of 0,3-1,8 μg /g. Antimony passes to groundwater with humic acids. Its concentration in natural water ranges from tenths of ng to 1 ng/mL. In waters polluted by municipal sewage or a landfill leachate its concentration may increase to few ng/mL, so it may be a monitoring parameter. Antimony com-pounds are readily taken up by plants, particularly when in a dissolved form. An increased content of antimony in plants, due to easy assimilation, can be expected at contaminated sites. (Niedzielski, 2000; Seńczuk, 1994).

Mercury (Hg) – (not listed in the table since, as a liquid metal, is not used in printed circuit boards; it can be found in e.g. energy-efficient light bulbs, thermometers, rectifiers and electrical contractors) enters human body mainly through a respiratory system and a digestive tract, but also through skin. About 80% of metallic mercury vapor inhaled is then retained in the human body; it enters a blood stream and is oxidized. Mercury is one of the highly toxic heavy metals. It shows teratogenic and mutagenic effects in living organisms and paralyzes a nervous system (ekologiaprace.wordpress.com).

Base metals

Aluminum (Al) – its absorption occurs by inhalation or ingestion. A daily dose of aluminum introduced with food is 10-100 mg. Gastrointestinal absorption in humans is small – less than 1%. In a healthy human body there is 50-150 mg of aluminum, half of which in bones and ¼ in lungs. Most of aluminum salts is converted to phosphates in a digestive tract and then excreted. Aluminum com-pounds in a living organism interfere with a number of metals and non-metals changing their bioavailability. In the human body aluminum competes with other elements such as zinc, iron, calcium and chromium. A mechanism of a neurotoxic process has not been well examined. Currently, it is believed that aluminum is toxic for humans mainly as a result of an occupational exposure (absorption of fumes and dusts). An occupational exposure may cause bronchopneumopathie, in a form of chronic nonspecific respiratory syndrome, lung fibrosis and pneumothorax. Vapors and fumes of aluminum as well as dust generated in production of aluminum powder are very dangerous, if inhaled. The fibrous weave pulmonary changes caused by a metallic aluminum powder are called pneumoconiosis aluminum. Aluminum dust in the alveoli is converted to hydrolyzed aluminum hydroxide causing cell divisions and couples with tissue proteins to form a colloidal complexes resulting in tissue hypertrophy and thickening of alveolar walls. Fibrous changes undergo cirrhosis, which in turn can lead to a large emphysema. The most common symptoms of silicosis are dry cough (mainly at night) and progressing exertional dyspnea. The period of the disease exposure lasts from several months to several years. Aluminium is also toxic for people with a renal failure, undergoing hemodialysis. In patients with a renal failure and peptic ulcer, symptoms associated with a lack of phosphate (anorexia, muscle weakness, osteomalacia) were observed after a long term treatment with aluminum compounds. People living in areas contaminated with aluminum get such symptoms mostly from soil and drinking water. Low concentrations of calcium and magnesium in water contribute to enhanced aluminium absorption from a digestive tract and its accumulation in a nervous system of humans. The studies on the impact of bioavailability of aluminum for fauna and flora and associated toxicity are of great importance in terms of an environmental exposure of the general population. Acid rains increase significantly an aluminum level in water used for food purposes (Seńczuk, 1994).

Copper (Cu) – is necessary for a proper functioning of humans body. It takes part primarily in oxidation-reduction processes as a coenzyme, regulates metabolism and transport of iron as well as collagen metabolism. The excess of copper in a human diet results in health impairment, it reduces hemoglobin, causes liver and kidney damage. Acute poisoning with copper salts are very rare. The toxic symptoms include damage to liver, kidneys, capillaries, pains and intestinal cramps. Death may occur after several hours of cardiac contraction, hypothermia and respiratory paralysis. Chronic poisoning results in congestion of nasal mucous membranes, gastritis and toxic symptoms, similar to those caused by zinc. Copper compounds act on skin causing itching, inflammation, they cause conjunctivitis, corneal ulceration and itching of the mucosa of the nose and throat. A surplus copper slows down chlorophyll biosynthesis in plants, however it is essential for a proper plant growth. Copper is found in enzymes and proteins involved in generative processes of plants, photosynthesis, respiration, and metabolism of nitrogen compounds. (Laskowski, 2004).

Iron (Fe) – is essential for living organisms. An adult organism has 4-5 g of iron in his body. Iron is a component of a hemoglobin molecule and is found in many enzymes involved in intracellular breathing. It influences enzymes, red blood cells, cell respiration, heart function, cell division, hormonal metabolism, development of muscle tissue, immune system and oxygen supply for cells. Its shortage leads to anemia and hair, skin and nails damages. Another symptoms include insomnia, fatigue, impaired concentration and memory, lack of appetite, pallor of skin, cold hands and feet syndrome, tinnitus, dizziness, frequent fainting, atrophic changes of tongue, gums and mucous membranes of the throat and stomach, muscle strength loss (www.ujk.edu.pl). A surplus of iron, as a result of improper diet or metabolism, can be very dangerous for humans. (http://bonavita.pl). It accumulates in the liver or pancreas poisoning the body.

Tin (Sn) – experiments on animals showed disturbances of hem biosynthesis and anemia. Organic tin compounds inhibit respiratory processes. The main symptoms of acute poisoning after drinking fruit juices stored in tin cans are: nausea, vomiting, diarrhea, general exhaustion and headache. Chronic poisoning occurs when people inhale tin; it manimainly as skin rushes and conjunctival irritations. Inorganic compounds of tin show low toxicity (Seńczuk, 1994).

Zinc (Zn) – plays an important role in plant metabolism. Both deficiency and surplus of this element impair the plants growth. Zinc deficiency in plants is generally observed when its content is below 20 mg/kg, while toxic effects when it exceeds 300 ÷ 400 mg/kg. Zinc deficiency disturbs metabolism of proteins, phosphates, carbohydrates and synthesis of RNA and DNA (impaired growth and reproduction of plants). An excess of Zn in soil and its intensive uptake by roots, as well as its deficiency, limit plant growth. The symptoms of high Zn concentrations in plant biomass include: chlorotic and necrotic changes in leaves, reduced photosynthesis, resulting in wrinkling of leaves and thus their slower growth. Zinc in most cases is taken up by plants proportionally to its content in soil, though both soil properties and plant species substantially affect its accumulation. Although zinc is an essential element in a human body its excess can cause metabolic disorders, disorders of a circulatory system and mental disorders. Acute poisoning with zinc com-pounds is rare, but people facing a long time expo-sure to zinc dust and zinc oxide may suffer: respiratory tract irritation, fever, dysfunction of the gastro-intestinal tract and anemia (Seńczuk, 1994).

Noble metals are inert to the human body and show bactericidal properties. They can be used to fill cavities, e.g. in bones, teeth or used in cosmetic and pharmaceutical industries.

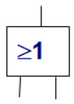
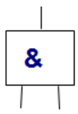
4.1. *Risk of environmental pollution*

In studies on an environmental pollution risk quantitative methods can be used only if a large and reliable database is available. If there is no a proper database, qualitative/quantitative or qualitative methods should rather be used instead. The group of qualitative/quantitative methods includes the logic trees methods (ETA, FTA). These are group methods in which possibility of overlooking any relevant fact is small. However, they require a good knowledge of the system. It should be noted that trees constructed by different people/teams may vary depending on an assumed level of detail, sys-tem understanding and available information. Below there are examples of applications of ETA and FTA methods as well as a qualitative matrix method.

FTA Method

The method of a fault tree (Fault Tree Analysis, FTA) is used to identify the causes leading to a specific undesirable event (fault). The event, known as a developing event, should be broken down to so-called basic causes. Therefore, starting from the fault, i.e. top event, using the method of top-down one descends down the tree to the original basic events. Logic gates (e.g. simultaneity gate AND, alternative gate OR, inhibit gate XOR, see Tab. 2) allow to specify the relationship between primary events (causes), which may lead to the undesirable event (fault).

Table 2. Logic gates used in the case study

Gate	Graphic symbol	Description	Probability of occurrence of an event (fault)
alternative OR		the output occurs if any input occurs	Sum of probabilities of input events (if they are independent)
simultaneity AND		the output occurs only if all inputs occur	Product of probabilities of input events (if they are independent)

The following is a proposed fault tree diagram for the top event Z0: contamination of soil and groundwater by e-waste deposited at a landfill. The method was first used as a qualitative method (Fig. 1). The developing events in the diagram were denoted as Z0, Z1, Z2 and Z3 while and the base events as B1, B2, ... B6. If municipality does not have incinerators, contamination of soil and/or groundwater may result from deposition of WEEE at illegal (Z1) or legal landfills (Z2). Contamination by a legal landfill (sealed, controlled) takes place only when the digestate from a composting plant will include WEEE (Z3) that releases dangerous substances (B5), and at the same time (AND gate) the site proves to be leaking (B6). The digestate will contain WEEE only when e-waste ends up in a container with a mixed fraction (B3), as not separated during earlier processes (B4).
FTA can also be used as a quantitative method. If probabilities of base events are known (at the bottom of the tree) then using the *down-top* method and Boolean algebra probability of events located at higher levels of problem decomposition can be found. At the final stage, the probability of occurrence of a top event would be determined, which can be assumed as a risk measure R = P (Z0). For a quantitative method the following risk ranges can be proposed: RA (acceptable) if $R \leq 0{,}005$; RT (tolerable) if $0{,}005 < R \leq 0{,}02$ and RN (unacceptable) if $R > 0{,}02$. Below, the actual probabilities of base events were assumed: P(B1)=0,2; P(B2)=P(B5)=1; P(B3)=0,2 P(B4)=0,05 and P(B6)=0,01. The *top-down* methods give the following probabilities of occurrence of developing events:

$$P(Z1) = P(B1) \cdot P(B2) = 0{,}2$$

$$P(Z3) = P(B3) \cdot P(B4) = 0{,}01$$

$$P(Z2) = P(Z3) \cdot P(B5) \cdot P(B6) = 0{,}0001$$

Finally, the risk assumed as probability of occurrence of the top event is
P(Z0)=P(Z1)+P(Z2)=0,2001,
while the same risk for a safe landfill (Z2) is acceptable.
As can be seen, the resulting risk R = P (Z0) is high. This result was influenced by the fact that high probability P (B1) was assumed (deposition of e-waste at illegal dumps). Reduction of risk can be achieved by raising environmental awareness (especially of rural populations), improving a WEEE collection system (e.g. a free pick-up of e-waste from households) and high fines imposed for abandoning waste at illegal sites (e.g. trenches, forests).

ETA Method

The event tree method (Event Tree Analysis, ETA) is used to identify scenarios (sequence of events) that can lead to undesired outcome as a result of the initiating event. Assuming that such an event took place, subsequent events and developments are analyzed; their occurrence (or not) in a specific order results in losses and lower security. After scenarios are identified, their outcomes can be predicted (qualitative method). If probability of occurrence of the initiating event and all developing events are known, probability of all scenarios can be determined as well as probability of a particular scenario (quantitative method). Probability of each scenario is determined by multiplying the probabilities of events present in this scenario.
In the study, the ETA method was applied for the initiating event: e-waste is discarded into a blue container with mixed fractions (event A, Fig. 2). As subsequent developing events the authors assumed: B-WEEE is not separated at a sorting site (e.g. metal separator is broken or lack thereof), C-WEEE is composted, D-WEEE is not separated from digestate (after composting) or slag, or filters did not remove harmful substances (after incineration). It can be seen that 3 out of 5 scenarios lead to environmental pollution. To determine the risk as probability of the

Figure 1. Fault tree for the top event *contamination of soil and groundwater by e-waste deposited at a landfill*, author's own work

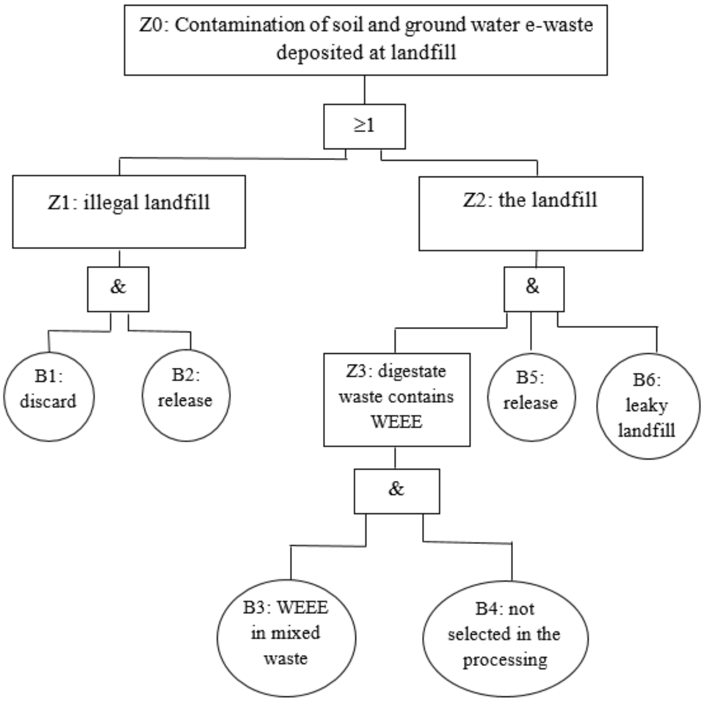
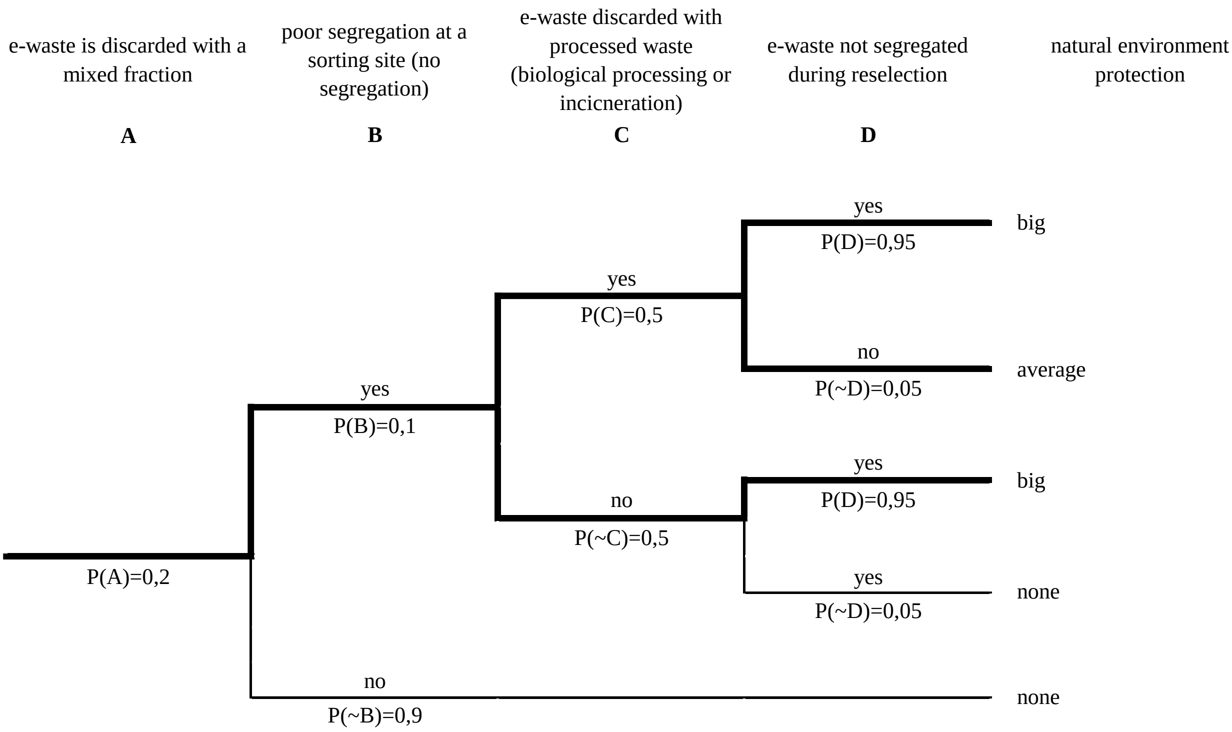


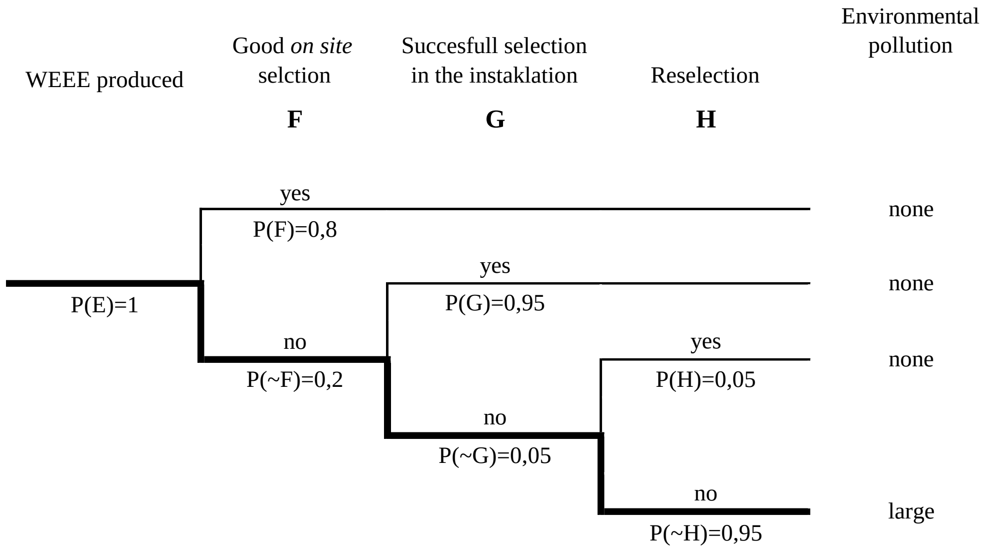
Figure 2. Event tree for the initiating event *e-waste gets discarded into a blue container with mixed fraction*, author's data



environment pollution three accident scenarios should be considered. Hence,
R=P{ABCD}+P{ABC~D}+P{AB~CD},
where ~ means an opposite event. The risk was $R = 0{,}2 \cdot 0{,}1 \cdot 0{,}5 \cdot (0{,}95 + 0{,}05 + 0{,}95) = 0{,}0195.$ It can be seen that the determined probability (risk) of the environment pollution if e-waste gets mixed with other fractions, although small, is not negligible and cannot be unconditionally accepted. In real life, the only way to reduce it is to reduce the probability of the initiating event. This can be done primarily by raising environmental awareness of people while simplifying the e-waste collection system.

A different tree of events can be created for each problem that can be differently targeted and have different applications. Below, the authors analyzed the

Figure 3. Tree of events for evaluation of efficiency of ee waste selection levels, author's data



impact of different levels of WEEE selection (Fig. 3); *selection completed successfully* means that WEEE is separated from mixed waste. It was assumed that e-waste is generated with probability of P (E) = 1 and a primary selection can be done *at source* (by the e-waste owner). In this analysis it was assumed that e-waste did not end up at illegal dumps nor at a scrap metal collection site. Due to environmental awareness of the WEEE user a proper action is taken and e-waste is turned over to municipal services with probability P (F) = 0.8. However, if electro waste ends up with mixed waste, so it is highly probable P (G) = 0.95 that it can be separated with magnetic metal separators. If not separated, then along with other waste it goes to the installation of mechanical-biological processing or to incinerators, and from there to a landfill. If during processing it will not decompose, it still may be captured (a very low probability P (H) = 0.05) during reselection in a mechanical-biological installation or can be finally disposed in incinerators (removed on filters or separated from slag). These three scenarios do not pollute the environment, as a result of initiation of one of selection levels. Pollution may occur if none of the above three selection works. Then, assuming risk as probability of the environment pollution, R=P{E~F~G~H} or $R = 1 \cdot 0{,}2 \cdot 0{,}05 \cdot 0{,}95 = 0{,}0095$. It can be seen that in spite of high probability values assumed for electro waste separation at levels P(F), P(G) and P(H), the final risk cannot be ignored. If probability of the initial selection *at source* increased to 0.9 due to better environmental awareness, risk would drop to 0.00475. The above method of selection evaluation is based on *analysis of protection layers* (AWZ) [PN-EN ISO 14121-1: 2008; IEC 60300-3-9; BS EN 1050: 1999) used in solving another risk problems. As it can be seen, a construction of the tree structure and scenarios (Fig. 3) is aimed at activation of some safety measures. In contrast, the first tree (Fig. 2) has been focused on the security damage and losses.

Matrix methods

A qualitative matrix method allows to estimate and evaluate risk by assigning it into one of the categories RA, RT or RN. Following the adoption of appropriate risk measures (e.g. $R = P \cdot S$) the actual range of each of the risk parameters (P, S) is divided into k classes; usually k = 3, 4 or 5 are assumed. Each class gets: rank (weight), descriptive term (qualitative e.g. rare event, large losses) and detailed specification (quantitative, e.g. frequency once every 3 years, losses over 100 thousand PLN). The principle is that more frequent events and more severe effects have higher ranks, while specifications should be defined individually for each event, according to the actual conditions. Then a risk matrix is prepared and the values for which risk is acceptable, tolerable and unacceptable are determined. When analyzing the particular problem, the risk measure is determined by multiplying the numbers (ranks) of the parameters. This is a relative value in a conventionally accepted scale (from 1 to k^2). After the risk evaluation, a plan to reduce risk for the range of RN and RT (if ALARP) is prepared or monitoring of RT and RA risks is planned.

The authors used the method to assess risk of environment pollution by bulbs, which were not delivered to a waste collection site (proper disposal) but were discarded into a blue container for mixed waste. The energy-saving light bulb contains about 4 to 5 milligrams of mercury, which is highly toxic. In addition, the bulb usually breaks in a bulk container and if so, once released mercury cannot be separated during further waste processing and is likely to be released to the environment despite all security measures (filters, seals, protective installations).

Here the classic risk measure $R = P \cdot S$ was adopted. For two risk parameters (P, S) k = 3 were assumed (Tab. 3, Tab. 4).

Table 3. Ranks of events that a not properly segregated bulbs pollute the environment [authors data]

class	frequency	detailed specification
1	Low	less that once every 3 years
2	average	less than once every 3 years but more than once a year
3	High	more than once a year

Table 4. Ranks of results [authors data]

class	results	detailed specification
1	small	up to 10 bulbs discarded to the mixed waste
2	average	10-30 bulbs discarded to the mixed waste
3	large	more than 30 bulbs discarded to the mixed waste

Then a risk matrix was prepared (Tab.5) with the following assumptions:

- Acceptable risk RA when R=1
- Tolerable risk RT when 2≤R≤3
- Unacceptable risk RN when R>3 or the highest class of results S=3.

Table 5. Risk matrix for the bulb discarded with mixed waste [authors data]

		S		
		1	2	3
P	1	1	2	3
	2	2	4	6
	3	3	6	9

Then two risks were evaluated arising from bulbs discarded to a blue container for the mixed fraction. These are:

1) risk R1, if the bulbs come from only one household; other city residents discard bulbs following utilization guidelines,
2) risk R2, if bulbs come from the entire city; all citizens behave in the same way and only about half of bulbs is properly utilized.

The analysis was performed for a small city. It was assumed that:

- city population is approx. 60 thousand with 15 thousand households,
- on average, 6 bulbs are burned in each household over 4 years, including car bulbs,
- on average, half of bulbs is discarded to a blue container for mixed waste (i.e. 3 bulbs in 4 years in a single household and 11,250 bulbs each year throughout the city).

For the assumed classes of frequency and effects the following results were calculated:

- $R1 = P1 \cdot S1 = 1 \cdot 1 = 1$– risk is acceptable RA,
- $R2 = P2 \cdot S2 = 3 \cdot 3 = 9$– risk is unacceptable RN.

Risk of environmental pollution with used bulbs from a single household may be subjectively considered as small; an individual decision will not matter to the environment because the effects of such event in e.g. a large city will be negligible. If, however, such decisions make a large number of people throughout the city, the result will be significant but only on a local scale. Though, if inhabitants of all the cities, towns and villages follow, the outcome will be of a global scale and environmental pollution will increase with time, which means that the burden of many individual, inappropriate actions can lead to a large, irreversible environmental changes. Such mechanism of a humans impact on the environment is called *the tyranny of small decisions* (Odum, 1982). Practically, the only way to reduce risk is to raise an environmental awareness of the population.

Conclusions

- Waste management systems and installations, including WEEE management, are subjected to risk as they are a possible source of harmful (dangerous, undesirable) events causing losses, damages or other adverse effects. To reduce a chance of serious scenarios or ensure losses minimization it is necessary to define risk, estimate its occurrence and then manage it in a proper way. The basic steps of risk management are: hazard identification, risk assessment, its evaluation and reduction, when risk is too high.
- With regard to the environment, the following risks can be discussed: pollution risk (chemical or landscape), risk of violation of the sustainable development principles and health risk.
- The article analyzes and assesses risk of the environmental impact in case of poor recovery and recycling of WEEE due to negligence or system malfunctions. Determination and assessment of risk in terms of sustainable development is an extremely important multi-faceted problem. It addresses the environmental threats and losses as well as the problem of depletion of natural resources, as a source for future generations.
- To prevent irreversible environment pollution some environmentally friendly rules of conduct should be promoted, beginning from early childhood. Additional work on promotion of anti-consumerism and environmental friendly policies should be carried out. Actions resulting from the lack of environmental awareness or problems with utilization of e-waste may be damaging to the environment. Accumulation of their individual effects of low significance may prove to be very harmful in the long run.

- The examples presented in the article have been simplified and the data have been estimated by experts, as the authors did not carry out a risk analysis for specific situations and objects but rather tried to propose the risk assessment methods.
- The analyses indicate that the problem of environmental pollution with e-waste is an important one and is becoming more and more urgent. Therefore, the risk problems highlighted in the article should be further explored.

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