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ORIGINAL PAPER

Risk assessment for sustainability in e-waste recycling in circular economy

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Abstract
E-waste is a hazardous concept for human health, environment and businesses, and therefore, risk assessment is essential to eliminate or reduce the negative effects of e-waste in a circular economy. Decision-making plays an important role during the risk assessment in e-waste recycling. This study aims to develop a decision tool under uncertain and risky conditions for achieving sustainability in electronic waste (e-waste) recycling in circular economy. Prospect theory and its aspects are integrated with the sustainability risk assessment in e-waste recycling. In order to evaluate the irrationality and risk attitudes of decision makers in a risky and uncertain environment, the prospect theory-based TODIM (acronym in Portuguese for interactive and multicriteria decision-making, i.e. Tomada de Decisão Interativa Multicritério) method for a previous computer disassembly problem is used. Using prospect theory, the relationship between loss aversion, reference point, framing and two selves effect, and sustainability dimensions is presented with a sustainability risk assessment point of view. Further, tasks of computer disassembly processes are prioritized by considering risk factors. The results showed that random access memory modules, motherboard and power supply are the highest priority risks based on the evaluation of listed twelve sustainability risks. In this study, it is suggested that prospect theory is suitable for decisions under risk and uncertainty, and it is applicable to integrate sustainability risk assessment and prospect theory in order to fulfil the gap of knowledge.

Graphic abstract
Relationship between prospect theory and sustainability risk assessment.

	Type	Loss Aversion	Reference Point	Diminishing Sensitivity
Business Factors	Gain/Loss	✓	✓	✓
Human Safety	Loss	✓	✓	-
Environmental Safety	Loss	✓	✓	-

Keywords Sustainability risk assessment · E-waste recycling · Circular economy · Prospect theory · TODIM

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Introduction

As one of the fastest growing sectors, electrical and electronic equipment production leads to increase in waste electric electronic equipment (WEEE), or say, e-waste (Babu et al. 2007; Neto et al. 2016). There is a direct relationship between the consumption rates of electronic goods and the amount of generated electronic waste (e-waste). Due to shrinking product life cycles, e-waste is a dynamic category of waste, as the new models of the products are introduced to the market, the consumers tend to purchase the latest versions, and therefore, adaptive recycling methods are needed (Olofsson and Mali 2017; Babar et al. 2019). This rapid growth in e-waste leads to the circular economy and sustainability-related concerns in terms of impacts on environment, society and economy.

More research is needed focusing on e-waste recycling activities (Bridgens et al. 2019). Advantages of e-waste recycling were categorized under economic, environmental and public health and safety benefits (Kumar et al. 2017). Four economic benefits of e-waste recycling are, firstly, recovery of e-waste with an estimated value of £ 48 billion, and based on value the recovered metals include copper, gold, silver, palladium, aluminium and iron. Secondly, concentration of metals in the e-waste stream is considerably higher than in the mining operations. Thirdly, e-waste provides the opportunity for reusing rare natural elements including gallium and indium. Finally, e-waste industry creates jobs and economic opportunities. In addition, three main environmental benefits of e-waste recycling are: Firstly, it reduces risks of disposal keeping hazardous waste out of landfills. Secondly, it decreases demand for new metal production and consequently reduces greenhouse emissions caused by metal production and finally energy saving by e-waste recycling. Adding to that, main public health and safety benefits of e-waste recycling are further stated as, the reduction in harmful effects of e-waste on public health and safety, including skin problems, damage to organs and bone structure, problems in nervous system, etc.

Among advantages or benefits of e-waste recycling, e-waste management is a complex activity. Managing e-waste contains many hazardous materials, and the process of e-waste recycling involves significant risks to the environment, human safety and business (Streicher-Porte et al. 2007) and also for circular economy. Moreover, recycling of e-waste, which is one of the effective strategies of circular economy, directly benefits to circular economy and it is crucial to have circular economy approach to gain more value based on sustainability (Reike et al. 2018). Therefore, a systematic approach is essential to evaluate risks of e-waste (Asante et al. 2019). In this sense, treatment of the e-waste is the most important subject in terms of minimizing negative impacts. Structured risk assessment for e-waste recycling is essential to understand the impacts on society and environment (Frazzoli et al. 2010). With this view, sustainability risk assessment (SRA) of e-waste recycling would be beneficial to deal with environmental, social and economic risks in an industrial context.

Different risks of e-waste recycling require crucial decisions due to the presence of uncertainty in the process. Decision-making plays an important role during the SRA, as assessing risks further seen as the main domain of such process (Chemweno et al. 2015). However, decision-making attitudes of human are usually neglected, and a theoretical integration is missing.

From this point of view, research question for this study is stated as: "How shall we incorporate decision making under risk and irrationality within SRA for e-waste recycling?"

This research aims to develop a decision-making method in uncertain and risky conditions in e-waste recycling system. To achieve this aim, firstly prospect theory, which is a behavioural theory that considers decision-making under uncertainty and risk, is proposed to examine sustainability risks of e-waste recycling. Secondly, a prospect theory-based multicriteria decision method, TODIM (acronym in Portuguese for interactive and multicriteria decision-making, i.e. Tomada de Decisão Interativa Multicritério), is used to evaluate listed risks. In order to show the applicability of this work, a computer disassembly problem is used as a case study, where computer disassembly tasks are evaluated according to relevant sustainability risks. Therefore, the novel point in this study is to evaluate the risks to the sustainability, within a system approach by integrating SRA and prospect theory to consider irrationality and risk attitudes of decision makers within the risky and uncertain nature of e-waste recycling system.

This study is structured as follows: in "Sustainability risk assessment (SRA) in e-waste recycling" section, the SRA in e-waste recycling is presented. In "Prospect theory" section, the details of prospect theory are given. In "Integration of SRA with prospect theory based TODIM" section, the integration of SRA and prospect theory is explained. "TODIM method" section gives the details of methodology, and "Case study" section presents the case study. "Results" section covers the discussion and conclusions.

Sustainability risk assessment (SRA) in e-waste recycling

Sustainability is used for describing the conditions of the society, environment and economy (Sikdar 2020). From the risk assessment point of view, sustainability risks have become growing concern for organizations. Thus, adequate risk assessment procedure is essential to deal with such risks. From managerial context, the SRA should be applied aligning environmental, social and economic risks under the roof of sustainability perspective (Manab and Aziz 2019). Further, Aziz et al. (2016) defined sustainability risks as ethical concerns related to social and environmental effects of organizational transactions. Dumay and Hossain (2019) suggested that SRA provides key information for companies and stakeholders to evaluate the performance of processes. The climate change, population growth, rapid technological developments and unpredictable sustainability risks are some of the reasons that increase the importance of SRA (Wijethilake and Lama 2019). Sustainability risks threaten the sustainable development of organizations causing long-term environmental, economic and social impacts. Therefore, identification and control of these sustainability risks by SRA are important for achieving sustainability goals (Valinejad and Rahmani 2018).

Sustainability plays an important role during the entire life cycle of system development, starting from raw material selection and use, manufacturing, packaging, transportation, distribution to customer, use, maintenance and finally disposal and recycle phases, where there is always a sustainability risk and a continuous SRA is essential (Anand et al. 2016). However, assessing sustainability risks on all levels is also beneficial for reducing the possibility of problems and helps to achieve sustainable development objectives (Bai et al. 2017). As in line with this view, this study focuses on one of growing global problem, e-waste recycling, where SRA is important to deal with the environmental, social and economic impacts of e-waste and threats on the circular economy.

E-waste is a hazardous concept for human health, environment and businesses. To manage risks of e-waste, a systematic process is needed to identify sustainability focused risks (Aziz et al. 2016). In this regard, SRA is applicable due to its holistic structure combining sustainability dimensions during risk assessment. The Directive of the European Parliament and of Council divides the WEEE into ten categories, large household appliances, small household appliances, monitoring and control instruments, medical equipment systems, electronic toys, electrical and electronic tools, lighting equipment, consumer equipment and information technology and telecommunications equipment (Directive 2012). After 2015, new Catalogue of WEEE Recycling was published, in which the following more categories were added: range hood, electric water heater, gas water heater, printer, copier, fax machine, monitor, mobile phone and single-machine telephone (Zeng et al. 2017).

E-waste includes a high variety of materials and contains a wide range of toxic substances that can contaminate environment and threaten human health and safety (Kiddee et al. 2013). E-waste is different from other industrial wastes, chemically and physically, where it includes both hazardous and valuable materials that need special handling and recycling methods (Robinson 2009). If e-waste is recycled or disposed without proper controls, negative impacts on environment and human safety are inevitable and also provide benefits for the circular economy. Moreover, the biggest advantages of the circular economy approach are to propose a regenerative system for e-waste recycling (Julianelli et al. 2020). Therefore, using SRA approach during e-waste recycling is beneficial for organizations and society to have systematic benefits.

Disposal of e-waste includes three main phases: the collection of the e-waste, the pre-treatment, including the activities as disassembly, separation of parts and shredding and finally extraction and purification of the valuable parts for recycling (Cecere and Martinelli 2017). The process of the separation of parts of e-waste can be done by using the automated machines or manually (Robinson 2009). Especially, in developing countries, dismantling and recycling activities are performed manually, which leads to generation of chemicals and plastics into the environment via water, air and soil (Caravanos et al. 2011). According to the study of Widmer et al. (2005), e-waste contains more than 1000 types of substances, many of which are toxic, such as mercury, arsenic, cadmium, selenium, hexavalent chromium and flame retardants. Examples of hazardous chemicals in e-waste are: heavy metals and metalloids including barium, mercury, copper, etc., brominated flame retardants including exabromo cyclodo decane (HBCDD) and polybrominated diphenyl ethers (PBDE), plastics including bisphenol-A, polychlorinated biphenyls (PVC) and lead glass (García et al. 2012; Purchase 2017). However, the potential health risks of e-waste affect each part of the human body, including central nervous system, digestive and urinary system, reproductive and endocrine system, respiratory system, blood, skeleton, and immune system, as summarized in the report of UN Environment (2017).

Among studies of specific group of e-waste, Lim and Schoenung (2010) draw attention to the effects of cellular phones wastes on human health and ecology and used triple bottom line (TBL) approach and named dimensions as consumer responsibility, corporate responsibility and government responsibility. Consumer responsibility includes environmentally responsible purchase behaviour and return products to recycling processes, whereas corporate responsibility focuses on design for environment, the take back system, environmental performance declaration, technology development and compliance with environmental regulations, and finally, government responsibility emphasizes the establishment of systems and institutions for waste management, coordination of stakeholders and environmental education (Lim and Schoenung 2010). The study of García et al. (2012) paid special attention on end-of-life computers in Mexico and presented both the chemical risks including toxic elements and the risks related to processes such as storing. Pinto (2008) also focused on computers under e-waste and divided potential risks of computer waste as occupational and environmental risks, where occupational and environmental risks are itemized for each component of the computer. In their study, details of hazards are also given. For instance, under human safety hazard physical hazards are exemplified as cuts from glass, acid contact with eyes, inhalation of chemical gases and contact with phosphor. Environmental hazards are further divided as air emissions, ground water toxicity due to lead, barium, emission of dioxins and heavy metals. (Pinto 2008). In addition, a recent study by Thais et al. (2017) was conducted for disassembly, transport and reassembly processes and the environmental risks of disassembly were defined under four subgroups: physical hazards, chemical risks, ergonomic risks and accident risks.

Crush or impact, explosion, environmental impact and environmental impact are presented as potential risks of disassembly in Liqui-Cel Membrane Contactors Disassembly and Assembly Manuel (2017), in which each risk is analysed for the disassembly processes. In the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) Report (2010), risks are further categorized as oxidizing flammable, explosive, infectious, radioactive, toxic, corrosive and spontaneous combustion. Avikal et al. (2014a, b) aimed to solve a disassembly problem, and used following criteria to evaluate tasks: task time, part demand, number of followers, revenue generated, part hazardous, state of material and fragility. The quality specifications/standards are also significant in recycling activities, and there are different kinds of specification for each type of waste, including e-waste, household plastic packages, batteries, etc. (Resource Association 2017).

Although it can be an accepted view that risks of e-waste recycling can be categorized under sustainability dimensions. Yet, various knowledge gaps related to SRA have been presented by Palousis et al. (2010) as: need for dealing with uncertainty by a risk management-based approach, the need for characterizing sustainability risk to identify and assess them, and linking entire product lifecycle with SRA. In addition to these, decision-making behaviour of human is generally neglected in SRA. However, in real life, decisions are not always rational, and the decision makers can be risk neutral, risk averse or a risk seeker. Therefore, in this study, it is suggested that prospect theory is suitable for decisions under risk and uncertainty. Further, the prospect theory-based TODIM method is proposed to develop a decision tool to evaluate SRA and fulfil the gap of knowledge.

Prospect theory

The way of people make decisions has long been a topic of research interests. Utility theory and prospect theory are two main theories that try to define how and why people make decisions. Utility theory is based on assessing the utility of gain by comparison of the utilities of two stages of wealth, while prospect theory assumes and shows that the outcome of decision-making under conditions of gains and losses is not symmetrical (Cochran 2001).

Utility theory was found as simple and lacks a moving part in terms of final states of wealth. The reference point is the missing variable, which is the earlier state relative to evaluation of gains and losses. The main difference between utility theory and prospect theory is that in Bernoulli's theory to determine utility, only the state of the wealth needs to be known, while in prospect theory, additionally, the reference state need to be known. Hence, prospect theory is a more complicated theory.

The three main principles of prospect theory were explained by Kahneman (2012) as follows:

- "Evaluation is relative to a neutral **reference point**, which is sometimes referred to as an "adaptation level". Better outcomes than reference points are named as gains, otherwise losses.
- **A principle of diminishing sensitivity** relates to sensory dimensions and the evaluation of change of wealth.
- **Loss aversion** is related to asymmetry between power of pain and pleasure. People generally take risks to prevent losses, where loss aversion explains variety in risk seeking and aversion. When directly compared or weighted against each other, "losses loom larger than gains".

Diminishing sensitivity for both gains and losses is represented by a salient feature it is S-shaped. The curves of the S-shaped are not symmetrical. The slope of the function differs at the reference point because reaction to losses is greater in effect than reaction to gains, which is referred as loss aversion.

- In problems where both loss and gain are possible, loss aversion causes highly risk-averse choices
- In problems where loss is inevitable and when compared to a larger loss that has low probability, diminishing sensitivity causes risk seeking.

There are two other effects which support the use of prospect theory in the decision-making process of e-waste recycling: Framing and Two Selves.

- Framing

Basically, framing refers to process through which people make sense of their external environment (Boettcher 2004). In other words, the approaches and reluctance of decision makers are affected by words, and it is expected that decision makers are to be biased towards the certain option in the case of KEEP, and against in case of LOSE. Therefore, preferences of decision makers are frame bound, not reality bound.

Depending on whether the consequences are bad or good, different selections in the two frames appropriate for prospect theory. When the output is good, decision makers are inclined to choose the certain things over the gamble. On the other hand, when the output is bad, they prefer to take risk. Hence, framing effect exposes that risk averse and risk seeking choices are not reality bound.

- Two selves

According to utility decision viewpoint, expected utility theory concerns the directions of rationality, which should rule decision utilities. Therefore, it is not about hedonic experiences.

Kahneman (2012) categorized experienced utility as the experiencing self and the remembering self. In this definition, experienced utility concerns perceived pain and pleasure. The experiencing self aims to answer the question "Does it hurt now?". On the other hand, the remembering self-answers the question "How was it, on the whole?"

Further, the retrospective assessments are insensitive to duration and emphasize the weight of two singular moments, peak and the end, much more than other moments.

Peak-end rule The global retrospective rating is foreseen well by the average of the level of pain/loss at the worst moment of the experience and at its end.

Duration neglect This refers to the procedures' duration which had no effect whatsoever on the ratings of total pain/loss.

In this sense, the integration of SRA for e-waste recycling activities with prospect theory is explained in the following section.

Integration of SRA with prospect theory based TODIM

The risks of e-waste recycling are studied within the scope of SRA approach. In e-waste recycling business factors, human and environmental safety need to be considered while assessing risks.

Utility theory is not suitable for decision-making under uncertainty and risk due to its sole dependency on outputs rather than the decision-making process. Features of prospect theory including loss aversion, reference point and diminishing sensitivity are very appropriate to explain irrationality and risk attitudes of decision makers. While examining risks of e-waste recycling activities under sustainability dimensions, potential behaviours of decisions makers according to prospect theory are summarized in Table 1.

Business factors can be considered with the objective of maximization, and it is a mixed gamble problem. In such situations, both gain and loss are possible, and therefore, loss aversion causes extremely risk averse choices. Potential gains or losses can be related to financial conditions, customers, sales rates, market share and reputation of the firm.

In business decisions, organizations tend to determine a reference point. In this case, organization's financial power, competitiveness and the reputation can be taken as a reference point to make decisions.

However, the marginal effect of loss in financial loss in sales and loss in market share decreases over time, which coincides with the rule of diminishing sensitivity.

Human and environmental safety are considered under the objective of minimization. For human safety, job satisfaction and commitment of employees, overall productivity, labour productivity, compensation costs, fines and reputation of the organization could be the potential business losses. For environmental safety, potential losses may be considered in terms of gas emission, carbon emission and loss of reputation.

Depending on the location of the organization, the attitude of the government, level of enforcement, and rules and regulations may be of the determinants of reference points for both the human safety and the environmental safety.

On the other hand, rule of diminishing sensitivity is not applicable for human and environmental safety, as environment and the losses affect the future generations' well-being; therefore, it is not appropriate to claim that there is a diminishing effect of losses.

Framing and two selves effects fit well with prospect theory. Further, the gambles are framed in terms of gains or losses. All three dimensions of our model are in line with framing and two selves effects. In Table 2, relationship

Table 1 Relationship between prospect theory aspects and sustainability dimensions

	Type	Loss aversion	Reference point	Diminishing sensitivity
Business factors	Gain/loss	✓	✓	✓
Human safety	Loss	✓	✓	–
Environmental safety	Loss	✓	✓	–

Table 2 Relationship between framing-two selves and sustainability dimensions

	Framing	Two selves
Business factors	✓	✓
Human safety	✓	✓
Environmental safety	✓	✓

between dimensions of sustainability and framing and two selves are presented.

When business factors are analysed in line with the framing effect, the reputation of the organization is emphasized and reputation may alter as a result of framing effect. For two selves, including experiencing and remembering, occurrence time and severity influence the effects. Notably, the change in market share, decrease in productivity, financial losses and reputation problems can be given as examples of when two selves effect is applicable.

The framing effect means that experts provided greater importance to the human safety and the environmental safety to be used to change perceptions. For instance, related to human safety, even though the level of occupational accidents is low, working conditions may be harmful for employees, causing potential chronic physical or mental problems. Additionally, environmental factors can also be framed easily. An example is focusing on improvements in emissions rate and presenting it to public, while disregarding the amount of solid waste generated.

However, for two selves effect, if experts have past work experiences about human and environmental safety, the remembering selves effect comes into prominence. Therefore, their decisions especially affected by peak-end rule and duration neglect.

Thus, the relationship was revealed between the three main principles of prospect theory and the three main dimensions of sustainability with a focus of e-waste recycling risk factors. Additionally, our models' relationship with framing and two selves effect, which are related concepts with prospect theory, are presented. With these explanations, an applicability of the integration of prospect theory and SRA in e-waste recycling is shown.

Next, an appropriate technique is needed for SRA of e-waste recycling. In risk assessment, there are many techniques for identification and evaluation; the most commons are as follows: brain storming, Delphi technique, checklist, preliminary hazard analysis, structured what-if technique, scenario analysis and business impact analysis. However in this study, focus is on risk evaluation techniques, and some of these are: hazard and operability (HAZOP), toxicity assessment, failure modes and effects analysis (FMEA) (Mangla et al. 2018; Panchal et al. 2018), failure modes and effects and criticality analysis (FMECA), cause and effect analysis, fault tree analysis, human reliability assessment, event tree analysis (Mangla et al. 2016), cause-consequence analysis, root cause analysis, layers of protection analysis and decision tree analysis. Moreover, multicriteria decision analysis (MCDA), risk indices and consequence/probability matrix are other techniques used in risk assessment (Valis and Koucky 2009; Mangla et al. 2015).

Bovea and Pérez-Belis (2012) categorized methods for evaluating environmental aspects under qualitative techniques, semi-qualitative techniques and quantitative techniques. Qualitative techniques include checklists, ten golden rules, materials, energy, toxic emissions (MET) matrix and matrix element checklist. Semi-qualitative techniques include environmental product life cycle matrix environmentally responsible product/process assessment matrix, ecodesign checklist method and product investigation, learning and optimization tool (PILOT). Finally, for quantitative techniques different types of life cycle assessments were given such as Markov models, Monte Carlo methods, qualitative uncertainty analysis, statistical models, component failure and initiating event models (Covello and Merkhoher 2013).

For environmental risk assessment, FMEA is one of the most widely used techniques. Zeng et al. (2010) integrated environmental and quality risks of project management using the FMEA method, Hu et al. (2009) integrated FMEA and fuzzy AHP for the risk evaluation of green component to hazardous substance. Sherwood and Shu (2000) used modified FMEA to support design for remanufacture in terms of waste stream analysis.

To sum up, to create SRA, the risk identification and risk analysis based on sustainability dimensions were conducted in e-waste recycling. To account for irrationality and risk attitudes of decision makers under risky and uncertain environment, the prospect theory is proposed. From this point of view, for risk evaluation the prospect theory-based TODIM method is recommended, which is explained in the following part.

TODIM method

The TODIM is a prospect theory-based discrete multicriteria method (Alali and Tolga 2019). The word TODIM is a Portuguese acronym in for interactive and multicriteria decision-making (Gomes et al. 2009). Unlike most of the multicriteria methods, which assume that decision makers seek the maximum global measure value for the corresponding solution, TODIM utilizes global measurement of value calculated by the application of prospect theory (Liang et al. 2020). From this point of view, the main reason to use TODIM in this study is, it focuses on the way of people make decision under risky conditions and accepts the philosophy of prospect theory.

As a prospect theory-based method, TODIM gives the shape the value function similar to gains/losses function of cumulative prospect theory as shown in Fig. 1, where gains and losses are always recognized concerning a reference point (Pereira et al. 2013).

The TODIM method is useful since it utilizes verbal scale in the evaluation hierarchy of criteria, relationship between alternatives, and fuzzy judgements (Tseng et al. 2014).

TODIM is a beneficial method for behavioural decision-making. The main benefit of the TODIM is to define the relative degree of dominance for each alternative using prospect theory-based utility function (Qin et al. 2017).

The TODIM method can be used for both the quantitative and the qualitative criteria, since the linguistic scales of the qualitative criteria can be transformed to cardinal ones, and both scales are normalized. Pairwise comparison is used in TODIM to measure dominance of alternatives over each other, and in the calculation part relative gain/loss values of alternatives are summed for each criterion (Gomes et al. 2009).

A decision matrix that involves alternatives and criteria should be defined as shown in Table 3. The normalization of matrix is further conducted.

In Table 4, $A_1, A_2, \ldots, A_m$ are m alternatives, $C_1, C_2, \ldots, C_n$ are n criteria, P_{ij} is the rating of the alternative A_i regarding criterion C_j, and $\omega = (\omega_1, \omega_2, \ldots, \omega_n)\ T$ is the weight vector related to the set of criteria $C = \{C_1, C_2, \ldots, C_n\}$, which satisfies the following conditions $\omega_j \in [0, 1]$ and $\sum_{j=1}^{n} \omega j = 1$.

Formulation of the TODIM method is summarized from the studies of Gomes et al. (2009) and Qin et al. (2017) as following;

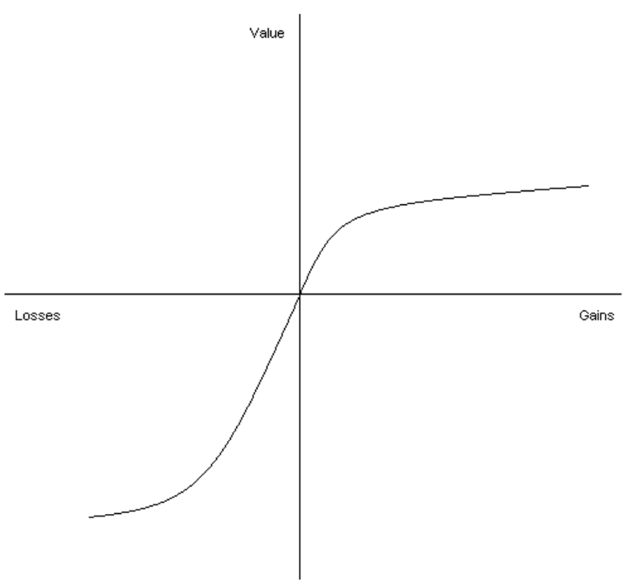

Fig. 1 Value function of the TODIM method

Table 3 Matrix of normalized alternatives' scores against criteria

Alternatives	Criteria			
	C_1	C_2	…	C_n
A_1	P_{11}	P_{12}	…	P_{1n}
A_2	P_{21}	P_{22}	…	P_{2n}
…	…	…	…	…
A_m	P_{m1}	P_{m2}	…	P_{mn}

Step 1 Relative weight ω_{ir} of the criterion C_j to the reference criterion C_r is calculated as following:

$$\omega_{jr} = \omega_j / \omega_r \quad (j = 1, 2, \ldots, n) \tag{1}$$

where ω_j indicates the weight of the criterion C_j and $\omega_r = \max\{\omega_j\}$.

Different methods such as analytical hierarchy process (AHP) or entropy can be integrated in this step for calculating weights for criteria. In this study, AHP is used.

Step 2 Dominance degree of each alternative A_i over each alternative A_k regarding to criterion C_j are calculated using Eq. (2).

$$\Phi_c(A_i, A_k) = \begin{cases} \sqrt{\dfrac{W_{jk}(P_{ij} - P_{kj})}{\sum_{j=1}^{m} w_{jk}}} & \text{if } P_{ij} - P_{kj} > 0 \\ 0 & \text{if } P_{ij} - P_{kj} = 0 \\ \dfrac{-1}{\theta}\sqrt{\dfrac{\left(\sum_{j=1}^{m} w_{jk}\right)(P_{kj} - P_{ij})}{w_{jk}}} & \text{if } P_{ij} - P_{kj} < 0 \end{cases} \tag{2}$$

while θ is named as the attenuation factor of the losses. A variety of θ lead to different shapes of the prospect theoretical value function in the negative quadrant. The range of the values of this parameter is $\theta > 0$, if $0 < \theta < 1$, then the effect of loss will increase; if $\theta > 1$, then the effect of loss will decrease.

Table 4 Specifications for computer disassembly tasks

Task	Definition of the removed component	Component demand
1	Top cover	300
2	Optic disc	550
3	Floppy disc	250
4	Storage unit	800
5	Back plate	400
6	PCI cards	500
7	RAM modules (3)	900
8	Power supply	350
9	Mother board	700

Step 3 Calculation of the overall dominance degree of each alternative A_i over A_k regarding to criterion C_j as shown below:

$$\delta(A_i, A_k) = \sum_{j=1}^{n} \Phi_j(A_i, A_k) \tag{3}$$

Step 4 Further, the global prospect value of the alternative A_i $(i = 1, 2, \ldots, m)$ is calculated:

$$\xi_i = \frac{\sum_{k=1}^{m} \delta(A_i, A_k) - \min \sum_{k=1}^{m} \delta(A_i, A_k)}{\max \sum_{k=1}^{m} \delta(A_i, A_k) - \min \sum_{k=1}^{m} \delta(A_i, A_k)}. \tag{4}$$

Step 5 In the final step, all alternatives are ranked according to their global prospect values. In this case, higher the value refers to better alternative A_i.

Case study

Advanced technological developments lead to increase in purchasing rates of electronic devices, including mobile phones and computers; therefore, reuse activities, including collection and recycle, is increasing vital in today's market place (Kahhat et al. 2008). Currently, e-waste is one of the priorities in waste management practices, and thus, decreasing the environmental effects of product from design phase to its end of life has become very important (Nnorom and Osibanjo 2008). Potential risks of e-waste should be considered while designing disassembly line due to its hazardous effects for human safety and environment. Therefore, disassemble is one of the important stages that should be included into SRA in e-waste recycling. From this point of view, this study is narrowed down to a disassembly problem as a part of SRA in e-waste recycling, where disassembly risks are considered for SRA.

This study involved a numerical example, a computer disassembly problem, formulated by Ilgin and Gupta (2012). The aim of the problem is to find the optimal sequence of the computer disassembly tasks. The information about the problem is given in Table 4.

As mentioned earlier, there are different types of risks in e-waste recycling processes. However, since the computer disassembly is taken as a numerical example, so it is important to specify the risks based on the problem for SRA. For this, a focus group discussion has been conducted with six experts including three from e-waste recycling company, two computer engineers and one chemical engineer. As a result, following risks are selected for this study to evaluate each part of the computer and used as criteria for TODIM implementation and shown in Table 5.

These given risks are used to evaluate tasks of computer disassembly processes and to prioritize tasks by considering risk factors. Briefly, these risks are used for the SRA and specified for the computer disassemble problem.

Table 5 Risk criteria

Risk criteria	Explanation	Author(s)
Revenue generated (C_1)	Revenue that can be gained through the part of e-waste	Avikal et al. (2013, 2014b) and Kazancoglu and Ozkan-Ozen (2019)
Part demand (C_2)	Demand for the each part	Ren et al. (2018) and Avikal et al. (2013)
Disposal cost (C_3)	Approximate cost of the disposal of each part of the e-waste	Dat et al. (2012)
Quality risks (C_4)	Seriousness potential quality problems during the recycling processes for each part of the e-waste	Zeng et al. (2010)
Ergonomic risk (C_5)	Caused by excessive physical effort, uncomfortable working environments and long working hours	Thais et al. (2017) and Kazancoglu and Ozkan-Ozen (2019)
Accident risk (C_6)	Caused by hazardous conditions in workplace and refers to the probability that an accident will arise	Thais et al. (2017) and Kazancoglu and Ozkan-Ozen (2019)
Crush (C_7)	To break the part through excessive force	Liqui-Cel Membrane Contactors Disassembly and Assembly Manuel (2017)
Lifting/moving hazard (C_8)	Risks related to lifting and moving of the parts force	Liqui-Cel Membrane Contactors Disassembly and Assembly Manuel (2017)
Flammable (C_9)	Flammable liquids, gases, or materials that burn very easily	ADR Report (2010)
Solid waste (C_{10})	It contains different kinds of materials that are discarded from industrial and community activities	Kazancoglu and Ozkan-Ozen (2019)
Oxidation (C_{11})	The process by which iron and steel rust	Chen et al. (2016)
Energy consumption (C_{12})	As one of the most significant features of environmental concerns	Tao et al. (2018)

Results

Explained totally, twelve risk factors were used as criteria and parts of the computer were used as alternatives. Microsoft Excel is used for the solution of problem via TODIM. Criteria 1–4 are business factors, criteria 5–8 are human safety risk factors, and criteria 9–12 are environmental risk factors. These criteria are presented in Table 5.

The part of the computer which are disassembled is the alternatives for TODIM and named as A1—Top Cover, A2—Optic Disk, A3—Floppy Disk, A4—Storage Unit, A5—Back Plate, A6—PCI Cards, A7—RAM Modules, A8—Power Supply, A9—Motherboard.

Numerical example of this study was developed by Ilgin and Gupta (2012). Thus, values of part demand were taken from their example. Rest of the risk factors were evaluated by expert's inputs in group decision-making. Since higher risk causes higher priority in disassembly tasks, in the scale, 5 means highest risk and 1 means lowest risk for evaluation.

Evaluation of alternatives against criteria is given in Table 6.

The AHP method was hired to calculate weights and was applied separately for business, human safety and environmental dimensions as a part of SRA. Same, six experts, who participated to the risk evaluation, are participated to the AHP implementation and asked to evaluate criteria. Weights of main criteria were found same, and rest of the weights of each criterion are presented in Table 7.

A sensitivity analysis is needed to verify the stability of the results, which can be done by varying values of attenuation factor of losses (Gomes et al. 2009; Zindani et al. 2017). With this view, sensitivity analysis was conducted by changing the value of attenuation factor of losses (Θ), aiming to determine whether or not it has an effect on the order or not. Due to alterations in risk attitudes, it has been thought that the result may vary for different attenuation factors. In doing so, $\Theta = 1$, $\Theta = 2$, $\Theta = 3$, $\Theta = 4$ and $\Theta = 5$ are used, respectively, for the sensitivity analysis and shown in Table 8.

Table 7 Criteria weights

Main criteria weights	Criteria	Criteria weights
0.33	C_1	0.135
	C_2	0.049
	C_3	0.097
	C_4	0.052
0.33	C_5	0.031
	C_6	0.194
	C_7	0.080
	C_8	0.028
0.33	C_9	0.056
	C_{10}	0.181
	C_{11}	0.017
	C_{12}	0.081

From Table 7, the changes in attenuation factors have no significant effects on the prioritization of the tasks, which reveals the overwhelming dominance of certain alternatives over others. Further, RAM modules, motherboard and power supply received the high priority in terms of risk assessment. The floppy disc needs less attention, according to the numerical results. However, it should be remembered that criteria selection can alter and depend on the product and it affects the numerical results. Therefore, implementation of the suggested methodology may give different numerical results, according to the needs of the organization.

Discussion and managerial implications

Due to decreased product life cycles and improvements in technological developments, e-waste is a rapid growing waste stream and one of the significant threats on circular economy (Babar et al. 2019). Increasing concerns about environment reveal the importance of the end-of-life phase

Table 6 Evaluation of alternatives against criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
A_1	3	300	2	2	4	4	2	4	1	5	2	1
A_2	2	550	2	4	2	2	3	1	2	4	1	3
A_3	1	250	1	3	2	2	1	1	2	4	1	3
A_4	5	800	3	5	1	1	1	1	1	4	1	4
A_5	2	400	2	2	4	4	1	1	1	5	2	1
A_6	4	500	4	5	3	3	1	1	1	4	1	4
A_7	5	900	4	5	3	3	1	1	3	5	1	2
A_8	3	350	3	4	3	4	1	3	4	4	1	5
A_9	4	700	5	5	2	2	1	1	3	5	1	4

Table 8 Results for the each attenuation factor

$\Theta=1$		$\Theta=2$		$\Theta=3$		$\Theta=4$		$\Theta=5$	
ALT	Normal global value	ALT	Normal global value	ALT	Normal global value	ALT	Normal global value	ALT	Normal global value
A_7	1.000	A_7	1.000	A_7	1.000	A_7	1.000	A_7	1.000
A_9	0.907	A_9	0.906	A_8	0.910	A_9	0.913	A_8	0.917
A_8	0.901	A_8	0.904	A_9	0.903	A_8	0.901	A_9	0.900
A_6	0.778	A_6	0.766	A_6	0.755	A_6	0.746	A_6	0.738
A_1	0.610	A_1	0.630	A_1	0.648	A_1	0.663	A_1	0.677
A_4	0.474	A_4	0.477	A_4	0.479	A_4	0.480	A_4	0.482
A_2	0.460	A_2	0.461	A_2	0.462	A_2	0.462	A_2	0.463
A_5	0.413	A_5	0.415	A_5	0.417	A_5	0.418	A_5	0.420
A_3	0.000	A_3	0.000	A_3	0.000	A_3	0.000	A_3	0.000

of products and the activities of reuse, remanufacturing, disassembly and recycling.

The SRA requires integrating the risks related to human, environment and business (Dumay and Hossain 2019). The SRA not only seeks to consider the organizations' financial performance, but also aims to maintain the longer and broader survival of the company (Aziz et al. 2016). Therefore, risks to be evaluated under SRA can act both independently and dependently. The dependent behaviour of these risks is caused by the interrelated aspects. Thus, the assessment of these risks should consider the interdependency. As asserted by the study of Asante et al. (2019), systematic approach is essential to deal with the risks of e-waste, and hence this study is based on systems approach to embrace both three dimensions of sustainability and different types of risks inherent in the e-waste recycling. Thus, the SRA and the proposed methodology are the reflection of system approach.

This study integrates SRA and prospect theory to consider irrationality and risk attitudes of decision makers within the risky and uncertain nature of e-waste recycling. Furthermore, this study contributes the literature by integrating sustainability and risk concepts in e-waste recycling, where a gap in the literature related to combinatory discussions in these subjects is stated by Rafi-Ul-Shan et al. (2018).

From the managerial viewpoints, e-waste recycling is an economically promising sector and it directly affects the circular economy. However, inherent potential risks should be considered by organizations to achieve sustainability by preventing environmental, human and business losses. Appropriate resource allocation is needed for risk prevention in a risk management process (Farrel et al. 2013). These resources include labour, finance, machinery and equipment. Organizations should allocate their resources considering the different risks. Considering environmental and human safety widens the number and scope of these risks. Hence, the proposed study can contribute to the planning and organizing activities of managers in a holistic manner. The proposed risk-based task prioritization process further enables effective resource allocation. In addition, organizations need to consider bottlenecks in resource allocation while prioritizing tasks in e-waste recycling. The proposed work can easily be applied on various different tasks in a wide range of industries dealing with e-waste and recycling. Furthermore, considering human risk attitudes during the e-waste recycling activities would be beneficial for organizations in terms of reducing potential effects on society.

In addition, it is apparent that the managers cannot achieve a sustainable growth and continuous improvement without conducting risk management. The risk assessment is an important part of risk management, and it should not only be applied at the strategic level but also needed at tactical and operational levels. Thus, the deployment and dissemination of the risk assessment are essential for long term success, sustainability and circular economy. Therefore, the proposed model in this study will support and equip managers aiming to integrate risk management and human decision process with an ultimate aim of achieving sustainability in e-waste recycling.

Conclusion

E-waste becomes a global problem, which threats the sustainability and circular economy. The focus of this study is evaluating the risks of e-waste recycling and developing a decision tool under uncertain and risky conditions. SRA is adopted as a tool to categorize risks of e-waste recycling, and decision-making attitudes of human is taken into the centre of the research question of this study, which is "How shall we incorporate decision making under risk and irrationality within sustainability risk assessment for e-waste recycling?". In order to achieve the purpose of this work, the prospect theory and its aspects are integrated to the SRA for e-waste recycling, and prospect theory-based TODIM method is used for a computer disassembly problem as a case study. In this work, the tasks of computer disassembly processes are prioritized considering risk factors. The results showed that, while RAM modules, motherboard and power supply received the high priority in terms of risk assessment, the floppy disc needs less attention. From a managerial context, it is revealed that integration of prospect theory with SRA is applicable for fulfilling the gap in knowledge related to considering irrationality and risk attitudes of decision makers within the risky and uncertain nature of e-waste recycling.

Among limitations, this study can handle the ambiguities and vagueness in the problem, but the results are not generalizable. Another limitation is that the proposed work has been applied in e-waste recycling.

Further, in order to increase the effectiveness of the proposed methodology the continuous monitoring of risks is needed and risk evaluation may be adjusted further. Organizational culture, strategic priorities and vision of the company, the demographic, social and educational background of the experts may alter the outcomes of this work, which appears as another limitation.

Future studies could apply the proposed methodology for other sectors and implement the suggested methodology on other real-life problems. Comparative analysis can be also conducted among different companies, sectors and even countries. Further, the scope of the proposed method can also be extended by covering circular operations other than recycling.

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