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Growing e-waste management risk awareness points toward new recycling scenarios: the view of the Big Four's youngest consultants

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Abstract

The e-waste sector is characterized by a rapid growth at global level and therefore involves an area not yet sufficiently investigated in its risk management dimension. This research fills the gap of the absence of a holistic approach to risk identification and assessment in e-waste management, suggesting a new Risk Awareness Indicator (RAI). An integrated Multi-criteria decision analysis (MCDA)-Analytic Hierarchy Process (AHP) is proposed to calculate the new index. Weights and values will be proposed by twenty Big Four's youngest consultants (generation-Z and millennials).

For e-waste, cyber risks related to personal data are critical in the collection phase, environmental risks in the transport phase, and financial and economic risks in the processing phase. Recycling scenarios pose less overall risk than landfill alternatives. The results can help policy makers to meet the circular economy targets set at the European Union level by implementing administrative and regulatory simplifications to support recycling supply chains and make them more efficient and resilient after the pandemic disruption. This work focuses on e-waste and the opinion of screenagers consultants, however the methodology used to design the RAI index makes it easy to replicate the analysis to other social settings and other waste supply chains.

Keywords: circular supply chain, e-waste management, generation-Z, millennials, multicriteria analysis, resilience, risk awareness, risk management

1. Introduction

COVID-19 has led to the elimination of many certainties, resulting in serious economic and social crises. At the same time, humanity is called upon to find solutions, to seize opportunities in a context where threats seem to predominate. The relationship between sustainability and resilience is the keystone, what is able to implement good practices and strategies, which can be extended in multiple contexts (Appolloni et al., 2021; D'Adamo et al., 2020b; Miceli et al., 2021). Evaluation of social aspects are important to consider in this sustainable transition (Caruso et al., 2020; Gholami et al., 2020).

Sustainable consumption and production are part of the Sustainable Development Goal 12 oriented to a reduction of waste generation also due to an approach based on prevention, reuse, recycling and recovery of waste (Hussain et al., 2020). New models of production and consumption are developed and the concept of waste conceived as a resource and therefore the use of landfill is the last choice in sustainable waste management (Arias Espana et al., 2018; Brown et al., 2018; Gangwar et al., 2019).

Within this framework, waste, and in particular electrical and electronic waste (e-waste), is characterized by a high growth rate (Isimekhai et al., 2017; Lin et al., 2020). The digital transformation is affecting not only businesses, but also the day-to-day lives of individuals (Gao et al., 2020). As a result, e-waste is growing more than any other waste category (Leung, 2019). Currently, recycling represents a sustainable circular practice for e-waste management (A. K. Awasthi et al., 2018; D'Adamo et al., 2019), involving the recovery of constituent materials for re-use in new industrial processes, in a circular economy perspective (Patil and Ramakrishna, 2020; Wang et al., 2018).

The global situation shows that some countries have advanced waste recovery practices (Islam et al., 2020), other countries have a low amount of waste generated but with the consequent risk of illegal dumping (Malinauskaite et al., 2017) and there is a need to increase traceability by promoting the proximity principle (Weber et al., 2019). In addition, similar to other industrial processes, e-waste recycling is associated with several risks, which affect the entire supply chain (Awasthi et al., 2019). These risks not only relate to the potential hazardousness of e-waste components (e.g., heavy metals), but also operational, regulatory, technological, human health, environmental and socio-economic aspects. Additionally, cyber risks exist with respect to personal and sensitive data and information captured within disposed electronic devices (Tozanlı et al., 2020). Thus, risk identification and management is critical for e-waste, similar to other consumer products.

Interest in risk identification has existed since ancient times, motivated by an impulse to prevent events that could negatively impact the well-being of humanity (Aven, 2016). In the modern era, risk is defined as the possibility of suffering damage caused by uncertainty in the behaviour of certain future variables (Boholm, 2019). To this end, organisations are faced with a variety of situations and risk factors that may impede progress towards their strategic goals. Increasingly, scholars and practitioners are engaging in the discipline of risk management (Fan and Xu, 2021; Longpré et al., 2020), proposing numerous methods of classification and assessment (Vujović et al., 2017). Within this context, risk mapping aims at selecting key risk categories for the purpose of risk assessment

(Yildiz et al., 2014). This procedure is essential for e-waste management, because the traditional approach to handling this waste mainly considers health, environmental and legal risks, while neglecting a multiplicity of risk factors that, if considered, could provide a more comprehensive knowledge framework to improve recycling operations. This practice could consolidate the firms' commitment to the sustainable development goals of the 2030 Agenda also through a socioeconomic framework that allows the e-waste supply chain to transition to an innovative, resource-efficient circular economy.

The identification of e-waste flows among several countries is a topic that has received little attention in the literature and the proposition of legal measures can facilitate the implementation of circular economy strategy by reducing negative impacts and increasing the value associated with the recovery of these materials (Xavier et al., 2021). Circular economy is able to satisfy the ever-increasing consumer demand on the environment and society (Cabrera-Codony et al., 2021; Shishkin et al., 2021). Circular business models should not only have a profit orientation, but balance economic growth and environmental stewardship with social mission (Fehrer and Wieland, 2021). Consequently, customers' purchase intentions are enabling factors towards the development of these models (Boyer et al., 2021). Another perspective that can support businesses is the smart circular economy in which the use of digital technologies improves efficiency in the use of resources (Kristoffersen et al., 2020).

Building on this, literature analyzes risk awareness in the context of circular economy models, with a focus on e-waste, in terms of current and future volumes (Ismail and Hanafiah, 2020; Kumar et al., 2017). Previous research on this topic has underlined the need to capture interactions between different risk categories (Hameed et al., 2020) and to generalise methods and results (Kazancoglu et al., 2020). Therefore, the main goal of this work is to conceptually develop and empirically validate an indicator, called the Risk Awareness Indicator (RAI), to assess the risk associated with e-waste recycling also in order to support appropriate consumption-oriented policies. Different risk components were analysed and applied to different phases of the e-waste management cycle.

Furthermore, recycling scenarios were compared to that of landfill disposal and evaluated according to firm size (i.e., small, medium, and large) and plant type (i.e., integrated, dedicated).

2. Literature analysis

In the present study, risk mapping was guided by a critical review of the scientific literature (Friday et al., 2018), involving a thorough but non-systematic analysis (Robinson and Lowe, 2015) of the most recent studies relevant to the research aim (Thomas et al., 2019). To this end, the following nine key risk categories were selected:

- *Operational risks*. These refer to contingencies causing a loss of resources in the pre-sales process; they are therefore non–revenue generating and inherent in all human-created and managed operating systems (Popov et al., 2016). Operational risks originate in a firm's processes, procedures and systems and have a potentially significant impact on people (Araz et al., 2020). The reduction of operational risk also helps remove any constraints on organizational and technological innovation.
- *Occupational risks*. These concern any circumstance capable of producing harm to humans in the context of work activity (Realyvásquez et al., 2018). The sources of the risk and the extent of the harm depend on the workplace and nature of the activity (Reiman et al., 2018).
- *Financial and economic risks*. Since the competitiveness of a firm is driven by the impact of financial variables on economic performance, it is necessary to consider economic risks linked with business activity (i.e., procurement, production, sales) that might reduce monetary profits (Spanagel et al., 2020). Financial risks are those associated with cash flows and payments, financing costs and treasury management (Valaskova et al., 2018). The focus on both help to innovate organizational culture especially for non-financial firms.
- *Social risks*. These arise in the relationship between a firm and its stakeholders, who claim compensation for the externalities produced by the firm's activities (Moura et al., 2019).

Social risks increase if the most influential stakeholders pressure the firm to restore social equilibrium (Graetz and Franks, 2016).

- *Technological risks*. These correspond to the potential damage or loss to assets, infrastructure and people that can occur due to the use of technology (Anderson and Felici, 2012). Further risk factors may relate to the uncertainty of a firm's technological innovation processes, involving investment decisions, future technological developments, innovation costs and market responses (Nechaev et al., 2017).
- *Supply chain risks*. This type of risk arises as the complexity of supply chains gradually grows (Namdar et al., 2018). The simultaneous increase in risk factors makes firms more vulnerable due to multiple elements such as: sudden changes in demand; difficulties or defaults faced by a supplier or distributor; supply disruptions due to natural, social or political events; and fluctuations in the price or availability of key inputs (González-Sánchez et al., 2020).
- *Cyber risks*. These arise when a firm conducts activity in cyberspace (Pogrebna and Skilton, 2019). Unlike physical threats, which produce immediate action, cyber threats may be difficult to identify and understand, while potentially having a significant impact on the firm's operations and external perception (Eling, 2020). In the age of digital innovation, it is therefore necessary to rethink approaches to risk management.
- *Compliance risks*. These are those risk categories related to the consequences of judicial, administrative or disciplinary sanctions; financial loss; or reputational damage due to non-compliance with applicable regulations that may affect business continuity. Regulatory compliance aims at preventing crimes and avoiding liability (Esayas and Mahler, 2015).
- *Environmental risks*. These represent the negative effects on ecosystems caused by a firm's operations. Increasingly stringent environmental regulations oblige firms to forecast and estimate the extent of damage (Ferrari et al., 2021) and make economic assessments to determine any compensatory measures. Such mitigation costs impact the competitiveness and profitability of the firm (Xie, 2012).

From a theoretical point of view, the literature highlights the multidimensional complexity of the concept of risk, but it lacks from an operational perspective, a holistic approach that considers the interactions between these dimensions. This research therefore aims to contribute to filling this gap.

3. Materials and methods

The MCDA methodology is frequently used by decision makers to evaluate multiple and conflictual alternatives. It functions by integrating the score associated with each alternative (i.e. the scoring criterion) with the weight assigned to the relevance of each criterion. In a data-poor scenario, a model based on the integrated MCDA-AHP methodology can support decision makers in a sustainable analysis context (D'Adamo et al., 2020a). The AHP methodology, developed by Saaty (1980), elaborates a list of priorities through pairwise comparisons based on expert judgments. This method is widely used in literature (Abdel-Basst et al., 2020).

The present work proposes a new indicator, called the RAI, to assess the risk associated with recycling e-waste. The RAI is a dimensionless indicator derived from the interaction among three variables: i) the risk value of each project (VP), ii) the weight of the risk component (WR) and iii) the weight of the e-waste management phase (WP). The different alternatives are compared through the assignment of a value determined according to a performance evaluated with respect to both the different risk components and the different management phases.

$$RAI_X = \sum_{Y=1}^{N_Y} RAI_{X,Y} \quad (1)$$

$$RAI_{X,Y} = \sum_{Z=1}^{N_Z} RAI_{X,Y,Z} \quad (2)$$

$$RAI_{X,Y,Z} = WP_Z * WR_{Y,Z} * VP_{X,Y,Z} \quad (3)$$

$$WP_Z = \sum_{I=1}^{N_I} SWP_{Z,I} / N_I \quad \text{with } Z = 1, \dots, N_Z \quad (4)$$

$$WR_{Y,Z} = \sum_{I=1}^{N_I} SWR_{Y,Z,I} / N_I \quad \text{with } Y = 1, \dots, N_Y \quad (5)$$

$$VP_{X,Y,Z} = \sum_{I=1}^{N_I} SVP_{X,Y,Z,I} / N_I \quad \text{with } X = 1, \dots, N_X \quad (6)$$

in which SWP = specific weight of the phase of e-waste management; Z = phase of e-waste management; N_Z = number of phases of e-waste management; SWR = specific weight of the risk component; Y = risk component; N_Y = number of risk components; SVP = specific value of each project; X = project (alternative); N_X = number of projects; I = interviewee; and N_I = number of interviewees.

3.1 Definition of alternatives

The challenges of climate change and the scarcity of natural resources require a paradigm shift to a situation in which even the e-waste sector is characterised by recycling, rather than landfilling. Recycling scenarios change according to three key variables: i) type of plant (i.e. dedicated or integrated), ii) plant owner (i.e. small-medium, large) and iii) economic potential of specific products (Rosa et al., 2019). With respect to the latter variable, the present study examined the cases of mobile phones and refrigerators, as these represent products with high and low values, respectively (D'Adamo et al., 2019). We identified seven scenarios for analysis:

- a mobile phone plant for a small-medium enterprise (X=1); a refrigerator plant for a small-medium enterprise (X=2); and an integrated plant for a small-medium enterprise (X=3);
- a mobile phone plant for a large firm (X=4); a refrigerator plant for a large firm (X=5); and an integrated plant for a large firm (X=6); and
- landfill use (X=7).

3.2 Definition of criteria

The literature review identified nine risk components, which the present study applied as criteria. This approach is typically used in the sustainable research context (D'Adamo et al., 2020a). The following criteria are used: operational, occupational, financial and economic, social, technological, supply chain, cyber, compliance and environmental. This choice was dictated by the need to include the insights that emerged from the literature review proposed in Section 2.

3.3 Identification of experts

Within the MCDA-AHP methodology, the identification of experts plays a key role, as they are relied on to provide both weights and values. In the present study, experts were selected from the generation-Z and millennial generations, known as '*screenagers*' – persons who were born digital and raised with ecological awareness. This is an aspect of promising relevance in a literature context because it is necessary to intercept new "value added". In addition, their occupations as young consultants within the 'big four' ensured a relatively inclusive view of e-waste management risks across different aspects of the business. The literature places great emphasis on generation-Z and millennials as categories of interest (Bollani et al., 2019; Kymäläinen et al., 2021).

Experts were identified through a message posted on LinkedIn, outlining the following criteria: i) younger than 30 years, ii) working as a consultant for one of the 'big four' accounting firms, iii) experienced in waste management issues and iv) passionate about the topic of e-waste recycling. It was further specified that the first five applications from each accounting firm would be considered. Accordingly, 20 experts were chosen for the sample, in line with the literature (Subramoniam et al., 2013). Interviewees were comprised of 12 men and 8 women from the European Union (i.e. Italy, Spain, France, Germany, Belgium, Austria, Netherlands, Sweden, Finland) and other countries (i.e. United Kingdom, Russia). Expert responses were collected through two survey rounds during November 2020–January 2021. The first round aimed at determining weights (i.e. WR and WP), while the second round aimed at assigning values to the criteria (i.e. VP). Each survey included the following stages: i) video call with the expert, explaining the purpose and methodology of the research, ii) demonstration of a practical example of a calculation and iii) collection of the expert's observations on the topic. The maximum time requested was one hour.

3.4 Assignment of weights to the criteria

The AHP model uses the eigenvalue method, which assigns a priority level to each criterion. The higher the weight, the more important the corresponding criterion (A. Awasthi et al., 2018). AHP weights are calculated according to a nine-point judgement scale (Saaty, 2008), and, in the present study, a normalising approach based on Belton and Gear (1983) was used to compare all values (Antonopoulos et al., 2014).

The AHP comparison matrix was conducted twice:

- The first procedure included three factors, comparing e-waste management phases (i.e. collection (Z=1); transportation (Z=2); treatment (Z=3)).
- The second procedure concerned nine factors, assessing risk components (i.e. operational (J=1); occupational (J=2); financial and economic (J=3); social (J=4); technological (J=5); supply chain (J=6); cyber (J=7); compliance (J=8); environmental (J=9)).

In the present study, the first survey was conducted using an Excel file supported by a Skype video call. According to the approach used by D'Adamo et al. (2020), experts were provided a file in which they could automatically check whether their judgment was trustworthy, providing a consistency ratio (CR). A CR measures the consistency of a pairwise comparison matrix, and its value must be lower than 0.10 (Saaty, 2008).

Each expert provided 38 responses, which were used to define both a 3x3 (WP) and a 9x9 matrix (WR). Equations (7) and (8) present the procedure using the case of the 3x3 matrix, in which experts were asked to indicate only three values: $V_{\beta\alpha}$, $V_{\gamma\alpha}$ and $V_{\gamma\beta}$. In more detail, scores ranged from 1– 9, where: 1 = equal preference; 2 = equal to moderate preference; 3 = moderate preference; 4 = moderate to strong preference; 5 = strong preference; 6 = strong to very strong preference; 7 = very strong preference; 8 = very to extremely strong preference; and 9 = extremely strong preference.

	α	**β**	**γ**	
α	1	$1/V_{\beta\alpha}$	$1/V_{\gamma\alpha}$	
β	$V_{\beta\alpha}$	1	$1/V_{\gamma\beta}$	
γ	$V_{\gamma\alpha}$	$V_{\gamma\beta}$	1	
Sum	SC_{α}	SC_{β}	SC_{γ}	(7)

	α	β	γ	Sum	Avg
α	$1/SC_\alpha$	$1/(V_{\beta\alpha}/SC_\alpha)$	$1/(V_{\gamma\alpha}/SC_\alpha)$	SR_α	AR_α
β	$V_{\beta\alpha}/SC_\alpha$	$1/SC_\beta$	$1/(V_{\gamma\beta}/SC_\beta)$	SR_β	AR_β
γ	$V_{\gamma\alpha}/SC_\alpha$	$V_{\gamma\beta}/SC_\beta$	$1/SC_\gamma$	SR_γ	AR_γ
Sum	1	1	1	3	1

(8)

α, β and γ represent the factors; $V_{\beta\alpha}$ is the value of factor β less one α; $V_{\gamma\alpha}$ is the value of factor γ less one α; $V_{\gamma\beta}$ is the value of factor γ less one β; SC_α is the sum of all values in the factor α column; SC_β is the sum of all values in the factor β column; SC_γ is the sum of all values in the factor γ column; SR_α is the sum of all values in the factor α row; SR_β is the sum of all values in the factor β row; SR_γ is the sum of all values in the factor γ row; AR_α is the average value in the factor α row; AR_β is the average value in the factor β row; and AR_γ is the average value in the factor γ row.

As indicated above, we aimed at verifying the reliability of the expert judgments, and therefore calculated the CR, as follows:

$$\lambda_{max} = SC_\alpha * AR_\alpha + SC_\beta * AR_\beta + SC_\gamma * AR_\gamma \quad (9)$$

$$CI = (\lambda_{max} - n)/(n - 1) \quad (10)$$

$$CR = CI/RI \quad (11)$$

λ_{max} is the largest Eigen value; CI is the consistency index; n is the number of factors; and RI is the random inconsistency value (n=3 → RI=0.58; n=9 → RI=1.45) - (Saaty, 2008).

3.5 Assignment of values to the criteria

A second survey round was conducted in this work, during which experts were shown the overall criteria ranking and asked to assign values to the criteria. Scores varied from 1 (worst) to 10 (best). Each expert provided 189 responses, which were used to define the third RAI component (VP), given that the other two components had been calculated in the previous step. An Excel file and Skype video call were also used in this second round.

4. Results

The results of this work were obtained by calculating the three components of the new indicator and, subsequently, aggregating the weights and values to calculate the RAI for each project alternative.

4.1 Assessment of weights to the criteria (e-waste management phases)

Experts' pairwise comparisons were collected and, starting with the normalised values obtained by the 3x3 matrices, all assessments were aggregated. Equal relevance was assigned to each expert. For example, expert 1 assigned greater weight to treatment ($SWP_{3,1}$ = 0.55) than to collection ($SWP_{1,1}$ = 0.35) and transportation ($SWP_{2,1}$ = 0.10). Figure 1 (all numerical values are reported in Table A1) shows the responses of all experts.

Figure 1

The findings underscore that all experts viewed the process through a systemic lens. Unsurprisingly, the treatment phase was considered most relevant – presumably because it is precisely in this phase that the most components and materials can be recovered (including both valuable and/or critical components as well as potentially harmful material). The objective of this phase is to minimise the amount of residue that is disposed of in landfills. In this regard, both technological innovation and subsidies can play a decisive role, but only in the context of a clear regulatory framework based on an assumption of responsibility and waste management near to the actual product consumption. In fact, technological innovation is an enabling factor for the circular economy both in terms of its environmental but also social and economic dimensions. However, technological progress should be accompanied by a re-engineering of production processes and a revision of purchasing and usage habits. It follows that policy makers can play a key role both in terms of industrial policy and in raising awareness of responsible consumption. All experts assigned the greatest weight to the treatment phase, ranging from 45–60%, with an average value of 53.50% (WP_3 = 0.535). Experts' perceived second most relevant phase was that of collection (also in this case unanimously), assuming that responsibility is not only assigned to producers and policy makers, but also consumers. The concept of sustainability depends on everyone's contribution being collected. Experts assigned a weight to this phase between 25–40%, with an average value of 33.75% (WP_1 = 0.3375). They noted that consumers may be more enticed if the principle was applied, as they would not have a cost to bear and indeed may receive an economic benefit for buying new, similar products. Finally, the transportation phase was not underestimated, and indeed improvements were thought relevant, with experts proposing actions unrelated to e-waste recycling (e.g. use of green fuels). Experts assigned an average value to this phase of 12.75% (WP_2 = 0.1275).

4.2 Assessment of criteria weights (risk components)

Within the first round, experts also compiled 9x9 matrices. Again, normalised values were aggregated, assuming that all interviewees were similarly relevant. Experts' pairwise comparisons referred to the risk components for each e-waste management phase. For example, expert 1 assigned greater weight to cyber risks ($SWR_{7,1,1}$ = 0.27) than financial and economic risks ($SWR_{3,1,1}$ = 0.23), with respect to the collection phase. However, the same expert assigned different weights to other phases: concerning the transport phase, the highest perceived risks were supply chain risks ($SWR_{6,2,1}$ = 0.28), followed by financial and economic risks ($SWR_{3,2,1}$ = 0.22); regarding the treatment phase, the highest perceived risks were economic risks ($SWR_{3,3,1}$ = 0.24), followed by technological risks ($SWR_{3,5,1}$ = 0.22). Figure 2 (see Tables A2–A4) presents all the weights referring to the risk components.

Figure 2

The results show that risk components varied according to the three phases of e-waste management (i.e. collection, transportation, treatment). However, financial and economic risks stood out as a common element across all phases, and were considered most important in 28 of the total 60 observations. More specifically, these risks received the values of 0.226 ($WR_{3,1}$), 0.225 ($WR_{3,2}$) and 0.228 ($WR_{3,1}$) for the collection, transport and treatment phases, respectively.

The concept of sustainability goes far beyond environmentalism, it is a more complex challenge involving multiple dimensions with the goal of maintaining a balance of ecosystems. Project implementation may have significant economic returns, but could lead to greater risks. Specifically, economic risks might be associated with the availability of subsidies, variation of costs and uncertainty linked to the price of components (e.g. printed circuit boards) and materials (e.g. Gold and Palladium).

At the collection stage, experts attributed significant weight to cyber risks ($WR_{7,1}$ = 0.219), highlighting that consumer may be conscious of risks to their privacy. Moreover, there was a strong correspondence between different technologies characterising electric and electronic equipment and the cyber risk component. Significantly, the other two pillars of sustainability received very similar weighting: experts reported that consumers must dispose of waste properly to not only protect the environment ($WR_{9,1}$ = 0.123), but also maintain social equity ($WR_{4,1}$ = 0.120). The first four weight components accounted for approximately 69%.

In the transportation phase, experts considered cooperation between parties important, identifying the key role played by supply chain risks ($WR_{6,2}$ = 0.218). Their main concern was a lack of accountability among various parties, which could potentially generate delays during this phase. The regulatory framework and contractual rules were thought to mitigate this risk. Even in this phase, experts considered environmental risks ($WR_{9,2}$ = 0.216) important, likely because successful environmental best practices consider the entire life cycle. The first three weight components accounted for approximately 66%.

Experts' analysis of the treatment phase was closely related to the concept of the circular economy. In this phase, economic risks were considered most relevant (as highlighted above), followed by environmental risks ($WR_{9,3}$ = 0.225). The recovery of all components and several materials is not easy, and the concept of zero waste is not always identifiable with zero use of landfill. In this regard, experts attributed significant weight to technology ($WR_{5,3}$ = 0.223) and innovation capable of providing solutions to difficult problems. The first three weight components accounted for approximately 68%.

4.3 Assessment of criteria values

In the second round of surveys, experts knew the average weights obtained in the first round. When data is available, values can be assigned to criteria objectively (Caruso et al., 2021); in the absence of data, expert know-how must substitute to make the results robust, with average values mitigating variability across individual judgements. For example, considering the scenario of a mobile phone plant for a small-medium enterprise during the collection phase, expert 1 assigned a value of 7 to financial and economic risks ($SVP_{1,3,1,1}$ = 7), while expert 2 assigned a value of 6 ($SVP_{1,3,1,2}$ = 6). Due to space constraints, we are not able to report all 3780 of the collected values here, but Table 1 presents the average values. Following the above example, the value associated with scenario X=1 for phase Z=1 was 6.60 ($SVP_{1,3,1}$).

Table 1

The first level of analysis concerned the distribution of the expert values, which tended to be rather uniform, showing peaks between 3–5 and low probability at the extremes. Specifically, the following percentage distribution was recorded for the individual value assessments: 1 (0.5%), 2 (7.1%), 3 (14.0%), 4 (14.2), 5 (14.3%), 6 (10.9%), 7 (10.7%), 8 (11.8%), 9 (10.6%) and 10 (6.0%).

Experts noted that they proposed values by comparing scenarios. In particular, it emerged that mobile phone plants had higher economic returns than refrigerator plants, and therefore higher associated risks. Attention was drawn to the presence of critical and valuable materials, which tend to be more relevant in e-waste recycling than the cost of disposing components containing hazardous materials. Although economic and financial risks represented only one of the nine components, they were obviously key to experts' approach. At the same time, integrated plants were thought to be potentially be more profitable than dedicated ones, given their ability to obtain saturation, exploit economies of scale, focus on technological advancement and benefit from relationships with various stakeholders. The return-risk pair was also proposed to compare firms. In particular, experts saw a key difference related to the ability of large firms to have large plants. The analysis of values confirmed the approach used by all experts, underscoring those higher values were associated with greater economic and financial, operational, occupational and environmental risks, while lower values were associated with compliance, technological and supply chain risks. No substantial changes were seen with respect to cyber and social components. Finally, approximately 70% of the values associated with the landfill scenario predicted the highest values (range 8–10). Specifically, in this scenario, all experts assigned the highest value to the environmental risk component in all phases.

Considering the seven alternative scenarios across three distinct phases, the highest average value was associated with environmental risks in nine contexts, economic and financial risks in six contexts, and cyber risks in four contexts, always with respect to mobile phone collection. Experts highlighted that the environmental risks associated with mobile phone e-waste can be very high, indicating that, while recycling can mitigate these risks, landfill disposal cannot. The point of view of the screenagers was clear. The pandemic picture provides an opportunity to see this moment of difficulty as an opportunity to put environmental issues at the centre of the agendas of all governments. It should be approached with a different perspective where the focus is on the resilience of systems. The circular economy is capable of producing new materials, new products, but this should not be seen as an addition to current actions, but as an alternative.

4.4 RAI for recycling e-waste

The RAI was derived from the product of three variables: i) WP (see Figure 1), ii) WR (see Figure 2) and iii) VP (see Table 1). According to equations (1) – (6), RAI_X was calculated for each alternative (Table 2-Figure 3-Figure 4). For example, considering the scenario of a mobile phone plant for a small-medium enterprise, three distinct RAI values were captured associated with the financial and economic component for each management phase, as follows:

$$\mathrm{RAI}_{1,3,1} = 0.3375 * 0.2260 * 6.60 = 0.503 \quad (12)$$

$$\mathrm{RAI}_{1,3,2} = 0.1275 * 0.2250 * 5.70 = 0.164 \quad (13)$$

$$\mathrm{RAI}_{1,3,3} = 0.5350 * 0.2280 * 7.20 = 0.878 \quad (14)$$

Subsequently, the single phases of e-waste management were aggregated, as follows:

$$\mathrm{RAI}_{1,3} = 0.503 + 0.164 + 0.878 = 1.545 \quad (15)$$

Finally, the values associated with each risk component were aggregated, as follows:

$$\mathrm{RAI}_{1} = 0.434 + 0.210 + 1.545 + 0.325 + 1.119 + 0.397 + 0.745 + 0.325 + 1.487 = 6.587 \quad (16)$$

Table 2

Figure 3

Figure 4

Analysis of the results showed that, despite the multiplicity of data and values collected by the experts, some clear trends emerged:

- Cyber risks were considered crucial within the waste collection phase, particularly with respect to mobile phones; this held true in both dedicated and integrated scenarios, as well as the landfill scenario. This result suggests sensitivity to consumers' personal data.
- Environmental risks were considered most critical during the transport phase, in both integrated scenarios and those dedicated to mobile phones. With regard to the landfill scenario, these risks were considered critical in the transport and treatment phases. This result highlights how the use of green fuels – a developing market – was favoured by experts as a solution to reduce environmental impact. Data on the landfill scenario highlighted the strong concern that this choice of waste management determined within civil society.
- Financial and economic risks were identified for all waste management phases in the management of refrigerator plants, highlighting potential investor concerns about waste management. In electronic waste characterised by low value products (i.e. refrigerators), it is more difficult to apply and implement circular economy models. With respect to the treatment phase in integrated plants, experts prioritised the economic component; the same held true for dedicated mobile phone plants with a large firm (while technological risks were thought to prevail in small-medium firms). Therefore, decision making choices tended to focus on economic aspects, but not in an absolute manner. Perhaps experts wanted to underline that a firm cannot be singularly focused on profits, but must also assume virtuous behaviour towards ecosystems.

The comparison of scenarios highlighted a correlation between risk and return. This suggests the potential for good business practice to identify a correct balance. The complexity of economic returns demonstrated variance according to the number of product types analysed (with integrated systems representing the simplest case, involving only two products). For this reason, analysis of risk components is fundamental to give solidity to the results, draw initial identifications and work towards minimisation.

Systems dedicated to refrigerators presented a lower RAI than systems dedicated to mobile phones, and this held true for both small-medium and large firms (RAI_2, = 5.416 < RAI_1 = 6.587; RAI_5 = 5.697 < RAI_4 = 6.828). Integrated installations capable of solving several issues were found to have higher risk (RAI_6 = 7.436; RAI_5 = 7.269). All recycling scenarios generated lower values than the landfill scenario (RAI_7 = 8.904); therefore, the rule of higher risk associated with higher return did not apply. Experts noted that the higher risks were easily explained from an environmental perspective, while, from an economic perspective, they held that a policy tool was needed to penalise agents who involved landfills in the end-of-life cycle.

An in-depth analysis of the indicators trends revealed an opportunity to disaggregate the findings and thereby identify the most relevant contributions. Considering the three phases of e-waste management, it emerged that the treatment phase received a weight ranging from 55–58%, followed by collection (weight ranging from 28–33%) and transport (weight ranging from 11–14%). No clear differences emerged between alternatives for managing e-waste at the end of life. Instead, economic and financial risks stood out amongst the nine components, with a weight ranging from 23–34% (with highest values linked to the management of refrigerators). Following this, environmental risks ranged from 21–24% and technological risks from 12–17%. Lastly, cyber risks had an average value of 4% for refrigerator waste and 11% for other scenarios.

5. Concluding remarks

5.1 Theoretical and methodological contribution

The present study has both theoretical and methodological implications. From a theoretical perspective, the RAI indicator that was developed and empirically validated proposes a weighted integration of specific criteria for each risk category. This approach introduces a holistic perspective to risk management with a double value: on the one hand, the main risk categories are considered and evaluated simultaneously; on the other hand, the time dimension is introduced, considering the entire life cycle of e-waste management. The resulting multidimensionality may prove more effective for risk management in complex contexts in which the handling of residual hazards implies the involvement of a plurality of stakeholders with divergent and sometimes conflicting expectations. In addition, the indicator's introduction of risk categories directly related to the pillars of sustainability (i.e., environment, economy, society) extends the potential applications of the model to include risk assessments of process and supply chain sustainability.

The analysis of expert opinions confirmed these theoretical assumptions. Young professionals, representing the future class of decision makers, expressed a particular awareness towards sustainability issues, and their emphasis of the vulnerability of personal data potentially contained in e-waste indicated a consideration of social sustainability, bringing into conflict individual and collective dimensions, as well as private and public domains. With respect to the methodological implications, the present research applied the techniques of MCDA and AHP to develop and validate the risk indicator, enabling it to support both multicriteria (deterministic) and multidecisor (probabilistic) decision making processes. Thus, the multi-criteria approach was given a probabilistic attribute, as is typical of risk assessments.

The application of the RAI is geared towards minimising the impact of risk from a sustainability perspective, where the closed supply chain must identify waste that is actually recyclable or otherwise reusable while minimising its sustainability footprint. In this context, the definition of new indicators is essential because it is able to provide ways of assessing useful decision-making in a multidimensional framework.

5.2 Managerial input and policy implications

In recent years, firms have implemented circular economy strategies for multiple – sometimes overlapping – reasons, including the potential for profits, regulatory compliance and strong environmental appeal. However, some circular economy and sustainability strategies involve the questionable practice – particularly among developed countries and resource consumers – of exporting waste to developing or underdeveloped countries, in some cases violating the Basel

Convention (which was designed to prevent the transfer of hazardous wastes). The present work highlights that, while the transportation of waste is indeed relevant, more importantly, it betrays the pursuit of sustainability. Application of the proximity principle, as well as the polluter pays principle, is fundamental. It would be appropriate to introduce a limit to the use of landfill by setting an ambitious target and economically penalising those who exceed it. Subsidy policies may also be essential for developing practices that mitigate market distortions that quantify carbon dioxide at a low price. Risk components influence the choices of decision makers, and quantitative-based methods, such as that proposed in this work, provide a ranking, highlighting critical risk components and identifying which areas require an intervention or more constant oversight. Therefore, the RAI is a potentially interesting tool for both private operators such as companies and public institutions as it can provide an overview of sustainability performance through risk assessment.

All personal products (e.g., notebook PCs) involve cyber risks, and the privacy of citizens should be guaranteed. Furthermore, while environmental risks represent the primary impetus for circular models, many options to minimise these risks are dependent on subsidies, which imply an increase in public spending. It is therefore necessary for decision makers to identify the economic conditions in which markets can create added value, and for firms to understand how to create competitive value within these markets. In fact, our experts noted that firms characterised by low cyber and environmental risks could attract new customers and/or strengthen ties with existing markets. Finally, product life cycles require detailed analysis, underlining financial and economic aspects. Both life cycle phases that imply greater cost and those that potentially produce greater revenue must be identified, as mitigation of the former and development of the latter would determine an increase in returns.

There is a strong positive correlation between increased returns and increased risk, but mitigation of risk components is possible. The circular economy provides a clear example of this, demonstrating that environmental risk components can be translated into reduced environmental impact. Here, a crossroads arises. The loss of economic opportunities is unsustainable, unless waste is transformed into a resource. However, as highlighted in the present analysis, the sustainable objective may not be achieved if there is a lack of attention to social risks. Such risks are often underestimated and considered a natural consequence of the other two dimensions of sustainability; however, this is not accurate. Involving various categories of stakeholders and gaining insight from younger generations will be decisive in reversing this trend. The main result of the present work is the introduction of a new indicator that, applied to the case of e-waste management, highlights the opportunities linked to this management within a circular model. However, the larger issue of e-waste management is very complex, involving several product types with different variants, hazardous components and materials of varying value, all with different weights attached to them. Last but not least, there are information campaigns aimed at increasing stakeholders' awareness of these issues and encouraging virtuous behavioural models.

Finally, some key policy insights emerge for the business world as follows:

- E-waste is a threat to climate change in the absence of adequate collection and recycling plants. Generation-Z and millennials are more attentive to the protection of ecosystems and identify circular economy models as a virtuous behavior also to counter climate change enabling the resilience of supply chain.
- Risk mitigation in the e-waste supply chain has multiple dimensions that need to be considered holistically and should include the use of policies that penalize countries that abuse landfills.
- The proximity principle, the polluter pays principle, subsidies for circular practices, information campaigns are policies to make our planet more environmentally friendly.

5.3 Limitations and implications for future studies

The present study includes some limitations. First, since the research aimed at capturing the perceptions of the next generation of decision makers (i.e., generation-Z and millennials) with respect to the risks generated by the management of e-waste, the results are clearly limited to this social group and only generalizable to comparable contexts. Second, the type of waste analysed represents a further limitation, as there are several other categories of waste (including industrial ones), which present a multiplicity of risks. Third, cybersecurity risk has grown exponentially during the pandemic period that has driven the use of electronic and digital devices. This must be correlated with the effects that these new habits of use can have on sustainability. Finally, the multidimensional character of the indicator could also include the assessment of resilience and its impact on the supply chain of different wastes.

The abovementioned limitations suggest an outline for future research. In fact, from a methodological perspective, the RAI is applicable to a diversity of contexts, as it does not suffer from any procedural or social bias. Therefore, risk assessment could be conducted with other socio-cultural groups, as well as for other categories of waste, products and services. In addition, risk mapping could be accompanied by a mapping of stakeholders who, in the analysed supply chain (e.g., e-waste), directly or indirectly influence the risk assessment decision making processes in different phases of the life cycle. In this way, risk management and stakeholder engagement actions could be integrated into a comprehensive corporate social responsibility strategy. This could represent a concrete solution for complying with environmental, social and governance criteria, which, in addition to becoming increasingly widespread among unlisted companies, also include risk assessment obligations.

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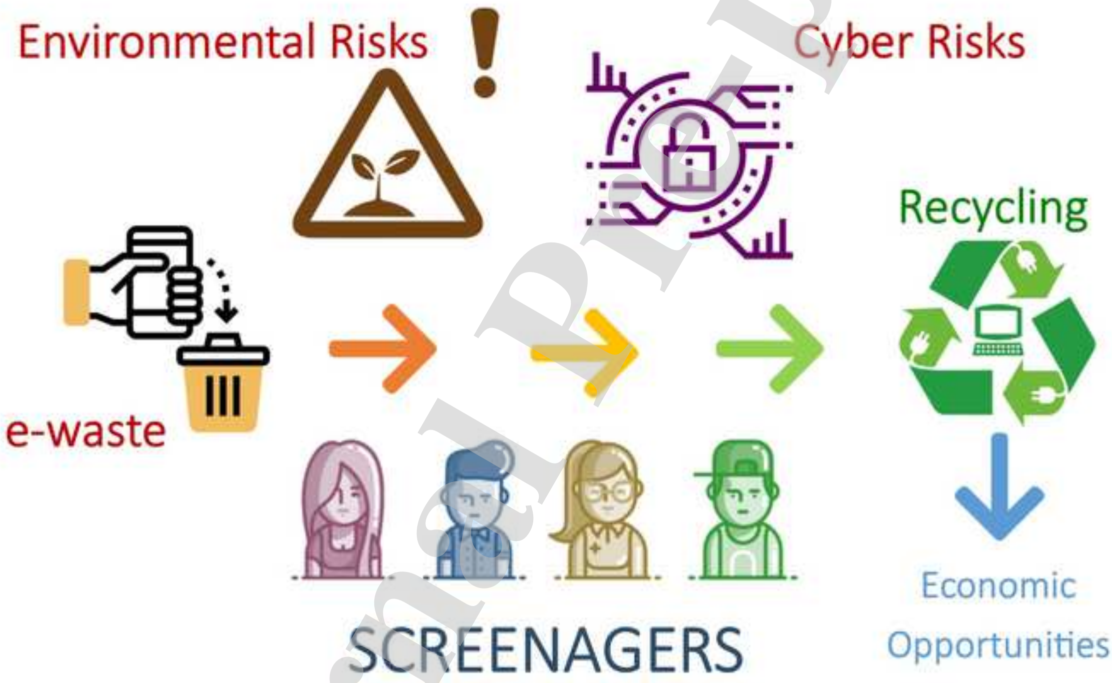
Highlights

HIGHLIGHTS

- Generation-Z and millennials are more attentive to the protection of ecosystems.
- Recycling plants reduce risks associated with e-waste management.
- Appropriate policies can mitigate the environmental impact of e-waste.
- Circular economy models as a virtuous choice in business strategies.
- Screenagers have a less ideological awareness of environmental challenges.

Graphical abstract



Figure

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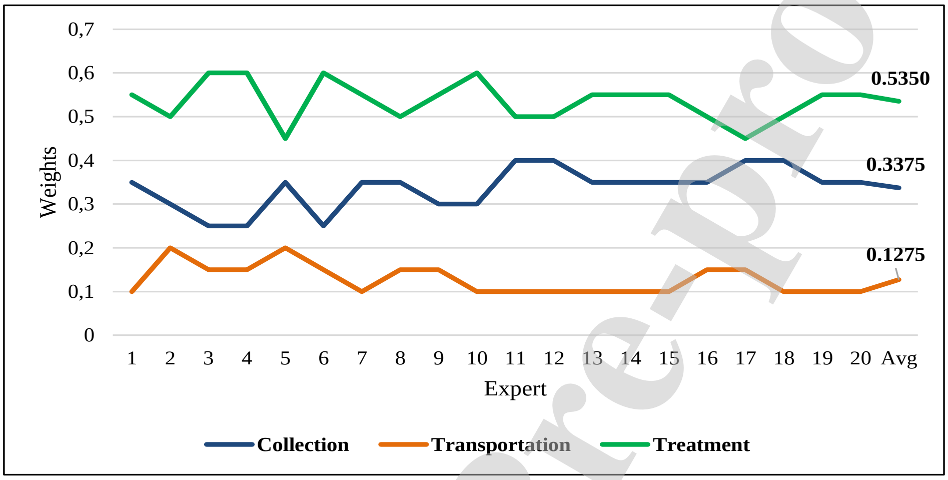

Figure 1. WP weights for each e-waste management

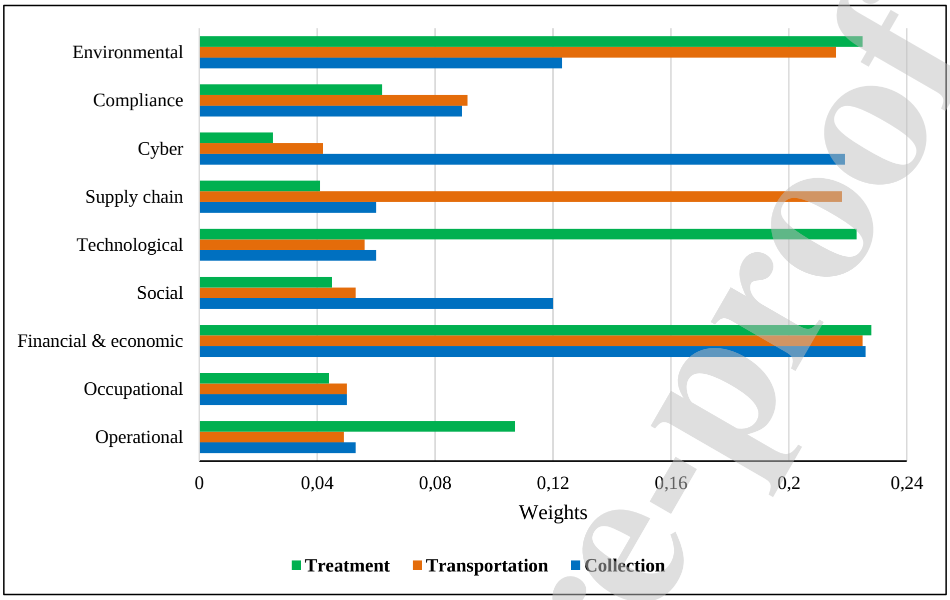

Figure 2. WR weights for risk components

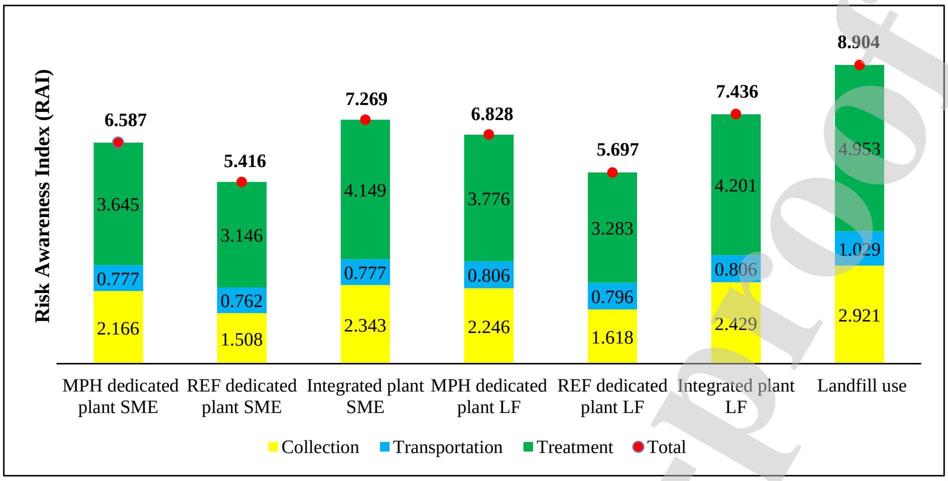

Figure 3. Distribution of RAI between e-waste management phases. Abbreviations: MPH (mobile phone), REF (refrigerator), SME (small-medium enterprise) and LF (large firm).

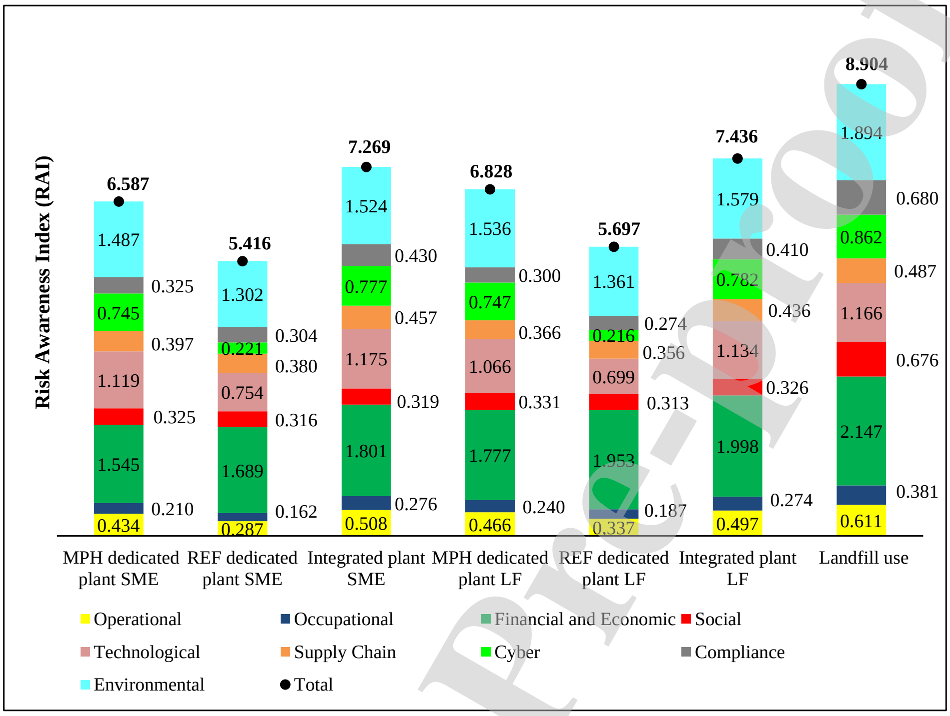

Figure 4. Distribution of RAI between risk components. Abbreviations: MPH (mobile phone), REF (refrigerator), SME (small-medium enterprise) and LF (large firm).

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Table 1. VP values for risk components

Scenarios	**Phases**	**Operational (J=1)**	**Occupational (J=2)**	**Financial and economic(J=3)**	**Social (J=4)**	**Technological (J=5)**	**Supply chain (J=6)**	**Cyber (J=7)**	**Compliance (J=8)**	**Environmental (J=9)**
X = 1	*Z = 1*	2.40	3.10	6.60	5.95	4.80	3.40	9.40	4.45	8.00
	Z = 2	2.60	5.70	5.70	2.70	5.20	7.75	3.10	4.90	7.85
	Z = 3	6.55	5.15	7.20	2.75	8.25	5.15	2.50	4.05	7.80
X = 2	*Z = 1*	3.85	3.30	6.05	5.35	2.45	3.50	2.55	2.75	7.55
	Z = 2	3.25	3.55	7.30	2.45	3.45	7.40	2.35	4.80	7.05
	Z = 3	3.45	3.55	8.35	3.45	5.70	4.70	1.50	5.00	6.60
X = 3	*Z = 1*	4.45	4.30	7.40	4.85	7.80	5.50	9.70	6.40	7.30
	Z = 2	2.60	5.70	5.70	2.70	5.20	7.75	3.10	4.90	7.85
	Z = 3	7.20	7.10	8.80	4.35	8.65	5.95	3.25	5.45	8.35
X = 4	*Z = 1*	2.95	3.50	7.75	6.05	4.20	2.90	9.40	4.10	8.10
	Z = 2	3.30	6.30	7.10	2.70	4.50	7.20	3.30	4.20	8.15
	Z = 3	6.85	6.00	8.05	2.80	7.95	4.90	2.60	3.85	8.10
X = 5	*Z = 1*	4.45	3.70	7.70	5.20	2.15	3.15	2.45	2.40	7.65
	Z = 2	3.70	4.10	8.50	2.55	3.20	7.05	2.50	4.50	7.30
	Z = 3	4.10	4.20	9.20	3.55	5.30	4.40	1.60	4.50	7.00
X = 6	*Z = 1*	4.65	4.60	8.40	4.95	7.55	5.25	9.75	6.15	7.55
	Z = 2	3.00	5.95	6.70	2.75	4.95	7.45	3.25	4.65	8.15
	Z = 3	6.90	6.75	9.55	4.45	8.35	5.60	3.30	5.15	8.65
X = 7	*Z = 1*	4.65	7.15	9.40	9.70	5.00	5.25	9.75	8.80	10.00
	Z = 2	4.30	7.40	9.25	8.55	3.70	7.45	4.45	8.55	10.00
	Z = 3	8.75	9.05	9.55	9.35	8.70	7.90	8.80	9.55	10.00

Table 2. RAI for e-waste management

Scenarios	Phases	Operational (J=1)	Occupational (J=2)	Financial and economic(J=3)	Social (J=4)	Technological (J=5)	Supply chain (J=6)	Cyber (J=7)	Compliance (J=8)	Environmental (J=9)	TOTAL
X = 1	Z = 1	0.043	0.052	0.503	0.241	0.097	0.069	0.695	0.134	0.332	
	Z = 2	0.016	0.036	0.164	0.018	0.037	0.215	0.017	0.057	0.216	
	Z = 3	0.375	0.121	0.878	0.066	0.984	0.113	0.033	0.134	0.939	
	Total	**0.434**	**0.210**	**1.545**	**0.325**	**1.119**	**0.397**	**0.745**	**0.325**	**1.487**	**6.587**
X = 2	Z = 1	0.069	0.056	0.461	0.217	0.050	0.071	0.188	0.083	0.313	
	Z = 2	0.020	0.023	0.209	0.017	0.025	0.206	0.013	0.056	0.194	
	Z = 3	0.197	0.084	1.019	0.083	0.680	0.103	0.020	0.166	0.794	
	Total	**0.287**	**0.162**	**1.689**	**0.316**	**0.754**	**0.380**	**0.221**	**0.304**	**1.302**	**5.416**
X = 3	Z = 1	0.080	0.073	0.564	0.196	0.106	0.111	0.717	0.192	0.303	
	Z = 2	0.016	0.036	0.164	0.018	0.037	0.215	0.017	0.057	0.216	
	Z = 3	0.412	0.167	1.073	0.105	1.032	0.131	0.043	0.181	1.005	
	Total	**0.508**	**0.276**	**1.801**	**0.319**	**1.175**	**0.457**	**0.777**	**0.430**	**1.524**	**7.269**
X = 4	Z = 1	0.053	0.059	0.591	0.245	0.085	0.059	0.695	0.123	0.336	
	Z = 2	0.021	0.040	0.204	0.018	0.032	0.200	0.018	0.049	0.224	
	Z = 3	0.392	0.141	0.982	0.067	0.948	0.107	0.035	0.128	0.975	
	Total	**0.466**	**0.240**	**1.777**	**0.331**	**1.066**	**0.366**	**0.747**	**0.300**	**1.536**	**6.828**
X = 5	Z = 1	0.080	0.062	0.587	0.211	0.044	0.064	0.181	0.072	0.318	
	Z = 2	0.023	0.026	0.244	0.017	0.023	0.196	0.013	0.052	0.201	
	Z = 3	0.235	0.099	1.122	0.085	0.632	0.097	0.021	0.149	0.843	
	Total	**0.337**	**0.187**	**1.953**	**0.313**	**0.699**	**0.356**	**0.216**	**0.274**	**1.361**	**5.697**
X = 6	Z = 1	0.083	0.078	0.641	0.200	0.102	0.106	0.721	0.185	0.313	
	Z = 2	0.019	0.038	0.192	0.019	0.035	0.207	0.017	0.054	0.224	
	Z = 3	0.395	0.159	1.165	0.107	0.996	0.123	0.044	0.171	1.041	
	Total	**0.497**	**0.274**	**1.998**	**0.326**	**1.134**	**0.436**	**0.782**	**0.410**	**1.579**	**7.436**
X = 7	Z = 1	0.083	0.121	0.717	0.393	0.101	0.106	0.721	0.264	0.415	
	Z = 2	0.027	0.047	0.265	0.058	0.026	0.207	0.024	0.099	0.275	
	Z = 3	0.501	0.213	1.165	0.225	1.038	0.173	0.118	0.317	1.204	
	Total	**0.611**	**0.381**	**2.147**	**0.676**	**1.166**	**0.487**	**0.862**	**0.680**	**1.894**	**8.904**

Conflict of Interest

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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