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Research article

Sustainable resilient E-waste management in London: A circular economy perspective

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ABSTRACT

The circular economy (CE) is reasoned to organize complex systems supporting sustainable resilience by distinguishing between waste materials and economic growth. This is crucial to the electronic waste (e-waste) industry of developed countries, and e-waste operation management has become their top priority because e-waste contains toxic materials and valuable sources of elements. In the UK, although London Metropolitan city boasts an ambitious sustainable resilience target underlying the context of CE, practical implementation has yet to be feasible, with few investigations detailing if and how the existing target implications enable industrial and social-ecological sectors to continue their performance functionalities in the face of undesired disruptions. In this paper, a dynamic Bayesian Network (dynamic BN) approach is developed to address a range of potential risks. The existing London e-waste operation management is considered as an application of study for sustainable resilience development. Through the utilization of dynamic BN, a comprehensive analysis yields a Resilience Index (RI) of 0.5424, coupled with a StdDev of 0.01350. These metrics offer a profound insight into the intricate workings of a sustainable system and its capacity to swiftly rebound from unexpected shocks and disturbances. This newfound understanding equips policymakers with the knowledge needed to navigate the complexities of sustainable e-waste management effectively. The implications drawn from these in-depth analyses furnish policymakers with invaluable information, enabling them to make judicious decisions that advance the cause of sustainable e-waste management. The findings underscore that the absorptive capacity of a sustainable and resilient e-waste operation management system stands as the foremost defense mechanism against unforeseen challenges. Furthermore, it becomes evident that two pivotal factors, namely “diversifying the supply chain” and “enhancing supply chain transparency,” play pivotal roles in augmenting the sustainability and resilience of e-waste operation management within the context of London’s ambitious sustainability targets. These factors are instrumental in steering the trajectory of e-waste management towards a more sustainable and resilient future, aligning with London’s aspirations for a greener and more eco-conscious future.

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1. Introduction

Electronic waste (e-waste) is a comprehensive term that refers to discarded electrical goods and end-of-life (EOL) electronic products such as personal computers, phones, tablets, laptops, TVs, printers, and other items. These products are often considered waste materials and are disposed of by users. The term "e-waste" is broad and encompasses a wide range of electronic products that have reached the end of their useful lives. Proper management of e-waste is critical to reducing the environmental impact of these materials and to promoting sustainable practices. Nowadays, society depends on electrical and electronic equipment (EEE) for daily life, and continuous use dominates people's daily activities [1,2]. E-waste materials include a potential source of valuable resources along with several hazardous elements, which can lead to severe environmental and human well-being problems [3,4]. Thus, a critical concern has been raised with the focus on circular economy (CE) when all EEEs evolve as outdated or defective. In addition, considering a global value of over 62 billion USD on e-waste materials [5], reliable and practical e-waste operation management becomes a significant challenge. The sudden global increase in EEEs caused more e-waste materials to be produced and abandoned in landfills [2]. In today's world, London (a complex system), a major global city, has the crucial role of being a leading financial, cultural, and political center in the European Union (EU), world economy, and international affairs. Therefore, implementing the existing e-waste operation management plans (sustainability approaches: maintained/prolonged use; reuse/distribution; remanufacture/refurbishment; and recycling [6]) without considering the multi-dimensional contributing parameters cannot be realistic and efficient, particularly when such a complex system has faced different types of undesired events, including natural or human-based disasters. To effectively handle e-waste, it is crucial to adopt sustainable resilience as a guiding principle for managing e-waste operations across various pathways within the circular economy. This means that developing sustainable and resilient e-waste operation management in the CE context is much more desirable.

In engineering domains, resilience is a multidimensional concept that has evolved over time, encapsulating the inherent capacity of a system to withstand and rebound from sudden undesired events while maintaining a stable state of functioning [7,8]. It consists of three key components: (i) resistance, which involves the system's ability to prevent and minimize the consequences of disruptive events; (ii) adaptation, enabling the system to recover functionality without external interventions; and (iii) restoration, focusing on recovering any functionality loss, sometimes with the acceptance of external measures [7,8]. Resilience also entails learning from past disruptions and acquiring knowledge for continuous improvement of system functionality over time [9–11]. While the core principles of resilience have been discussed in previous literature, its application and nuances can vary across different contexts, signifying an evolutionary refinement of a concept rather than a wholly new one. As such, resilience represents not just a single static idea, but rather a dynamic concept that has been shaped and adapted to address specific challenges in diverse fields, highlighting its versatility and relevance. Considering London's aspirations [12] to become a leading sustainable city through ambitious objectives (e.g., to be a zero-carbon city by 2050; to have the world's first National Park City; to have more than 80 % of travel be completed by walking, cycling or using public transport by 2041; and to become sustainable and resilient, especially with respect to climate change impacts), it is evident that a progressive and reliable, sustainable and resilient e-waste operation management is essential for London's broad policies to be executed successfully in the lens of CE.

In the context of this study, "system resilience" pertains to the ability of a complex system, such as the e-waste management system within the circular economy framework, to not only withstand and recover from disruptions but also adapt and thrive in the face of challenges, shocks, or unforeseen events. This includes the system's capacity to absorb, adapt, and restore its functionality while maintaining its core operations and sustainability. Quantifying system resilience involves the use of various resilience metrics and corresponding formulations, which have been developed across different domains to assess and evaluate the resilience of complex systems [13–17]. These metrics provide a structured approach to measure the system's ability to absorb shocks, adapt to changing conditions, and recover to a functional state, ensuring its long-term viability and effectiveness. By employing these metrics, the insights

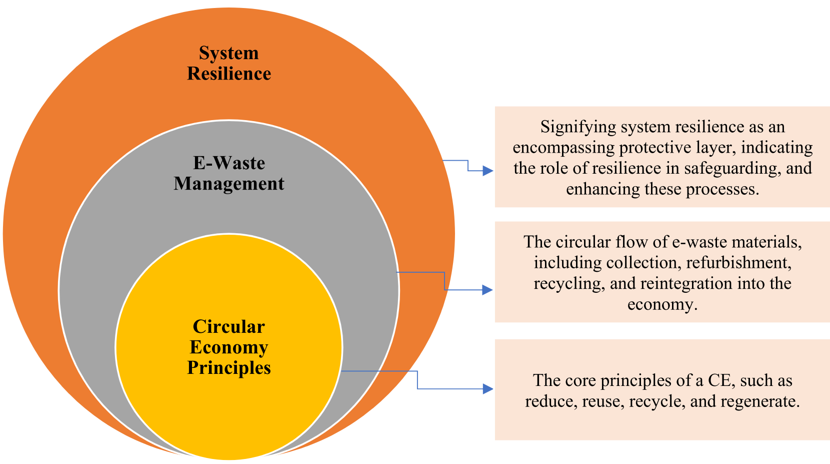

Fig. 1. The interconnection of circular economy, e-waste management, and system resilience.

come up into the robustness and sustainability of e-waste management practices within the CE, ultimately contributing to more informed decision-making and the enhancement of this crucial facet of sustainable resource management. In addition, the interconnection of circular economy, e-waste management, and system resiliencies depicted in Fig. 1.

An overview of the concept of resilience suggests that it is a complex, multi-dimensional, and time-dependent element that is uncertain and heavily influenced by the system's performance loss [18]. Thus, an influential diagram within the capability of causality and interdependency analysis could effectively capture the aforementioned inherent feature of resilience. Dynamic Bayesian Networks (dynamic BN), a powerful decision-making tool, can be used to model and analyze the resilience of complex systems where uncertainty and complex relationships among contributing factors exist. It can also identify critical elements (i.e., resilience characteristics) or vulnerabilities in the system that most likely lead to undesired disruptions. Dynamic BN allows reasoning under uncertainty, which enables updating the structural model and evaluating the system's resilience in real-time once new evidence or observations becomes available. As a result, all dynamic BN features make it a robust technique for continually monitoring and improving the resilience of complex systems, particularly in dynamic environments.

Fig. 2 illustrates the number of publications and citations on integrating BN and resilience in different application domains. It can be observed that both publication trends and citations have increased over the last decade, especially after the year 2020. Studies using the integration of BN to assess resilience are expected to continue to grow at an increased pace in the following years. Table 1 provides an overview of published research articles integrating BN into the resilience concept in different application domains.

In addition to the presented overview, in a study conducted by Beraud et al. [34], a functional analysis was carried out to assess and improve the resilience of waste management systems in applying household waste management chains. Lee et al. [35] proposed a multi-criteria geographic information system (GIS) approach to improve flooding resilience, considering which potential sites have relatively superior suitability ratings. The degree of construction structures for post-disaster destruction is being examined to promote sustainable post-disaster waste management and future resilience [36]. Using a cost-minimization model and resilience characteristics, a highly resilient reverse logistics network is designed for Japanese material cycling [37]. In their research, Mamashli et al. [38] proposed a multi-objective mixed-integer linear programming model aimed at maximizing the logistics system's social impacts and resilience while minimizing environmental effects, total costs, and transportation risks. In another study, Wakabayashi et al. [39] developed an economical and environmental approach to evaluate a waste disaster management system in Mie Prefecture, Japan, to ensure resilience of the system in disasters. Finally, the study conducted by Irshad Mari et al. [40] presented an optimization model to assess the resilience of a sustainable supply chain in terms of location risks and embodied carbon footprints. Cooperating resilience and CE can be demonstrated in the resilience supply chain, including the COVID-19 era [41–43], recycling practices [44], dynamic remanufacturing capability [45], digital technologies [41], blockchain technology [42], and more.

As can be observed from the previous studies, many attempts have been carried out regarding e-waste management, especially in developing countries. However, practical studies bridging sustainable resilience and CE are rare and sparse [26]. The critical questions remain unanswered, including how effectively the resilience characteristics may be integrated into the business of CE practice and how developing and pursuing a sustainable and resilient framework may influence industrial and social-ecological sectors. The CE-based studies considered constructing social-ecological system resilience, while the concept of resilience indicates an essential need for interaction among multiple levels of the complex system. Yet, the empirical research and conceptual study to support the mentioned consideration is lacking. In addition, the existing works have developed managerial explanations and practices addressing complex

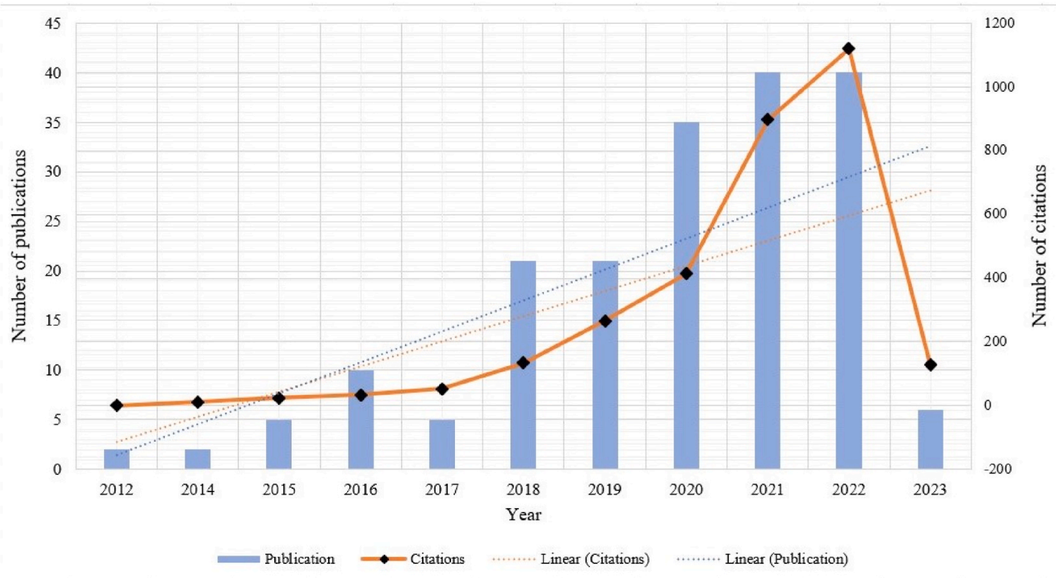

Fig. 2. Distribution of published documents and the corresponding number of citations over time [source: Web of Science (WoS) by the end of February 2023, search keywords: TOPIC ("Resilience" AND "Bayesian Network")].

Table 1
An overview of published research articles with the integration of BN in the resilience concept in different application domains.

Row	Reference	Remarks	ACY[a]	Case Study
No. 1	Hosseini and Barker (2016) [19]	- The resilience of critical infrastructure is modeled using BN. - An intermodal transportation network is identified as the most critical component.	23.13	Inland waterway ports
No. 2	Hosseini and Barker (2016) [20]	- Different resilience-based supplier selection criteria are taken into account. - BN is used to quantify supply chain resilience by effectively modeling the causal relationships among the supplier selection criteria.	20.75	Supplier selection in the context of supply chain management
No. 3	Ojha et al. (2018) [21]	- The risk behavior is measured in supply chain risk propagation. - The vulnerability and adaptability of the supply chain network are assessed using BN.	20.17	Supply chain risk propagation
No. 4	Hosseini et al. (2020) [22]	- The recovery and vulnerability of suppliers are modeled using an integration of dynamic BN and Discrete-Time Markov Chain. - The propagation behavior of supplier disruption is also simulated. - A ripple effect of supplier disruption is quantified using a proposed metric.	15.4	Ripple effect modeling of supplier disruption
No. 5	Hosseini et al. (2016) [23]	- An approach is proposed to assess the resilience of supply chain contributing factors. - BN assesses and quantifies sulfuric acid manufacturers' resilience.	8.75	Sulfuric acid manufacturer
No. 6	Hossain et al. (2019) [24]	- The electrical power system risks are addressed utilizing BN. - The reliability and backup power source are the prime factors in the understudy system.	11.4	Electrical infrastructure system
No. 7	Hossain et al. (2019) [25]	- BN is used to assess the resilience of the interdependent electrical network. - The interdependent electrical network is classified considering different types of resilience characteristics.	11	Service deep water port
No. 8	Hosseini et al. (2022) [26]	- The vulnerability and recoverability of the system are assessed using BN. - A balance between risk mitigation and recovery capabilities is suggested to supply chain managers.	24	Supply chain in an open-system context
No. 9	Garvey and Carnovale (2020) [27]	- The tension between under-supply and system breakdown is explored using BN. - A simulation study is conducted to understand the nature of this trade-off concerning the minimization of the potential risk.	7.75	The rippled newsvendor
No.10	Tang et al. (2020) [28]	- The resilience of urban transportation is quantified using hierarchical BN modeling. - The reconfiguration is a critical factor in rebuilding and adapting resilience characteristics.	6.75	Urban transportation systems
No. 11	Dong et al. (2020) [29]	- The vulnerability of the flood control infrastructure is assessed using BN. - The failure cascade is simulated as a matter of probabilistic model. - It helps decision-makers with scenario planning and real-time inundation prediction purpose.	4.5	Flood control networks
No. 12	Sakib et al. (2021) [30]	- Bayesian belief network is used to predict and assess disasters in the oil and gas supply chain industry. - It is identified that the technical factors and political factors have the highest and lowest impacts on the oil and gas supply chain.	7.67	Oil and gas supply chain
No. 13	Liu et al. (2021) [31]	- Dynamic BN is used to estimate the risk of disruptions. - A nonlinear programming formulation is used to materialize the utilization of dynamic BN.	5.75	Supply chain ripple effect
No. 14	Wu et al. (2018) [32]	- BN and Delphi methods are used to assess the rapid-fire evolution process and the relevant consequences. - The work provides insight into a more realistic analysis of fire disaster reduction.	3.83	Underground subway stations
No. 15	Cai et al. (2018) [33]	- BN is used to assess the interactions among different resilience characteristics and to address the natural-human system, - A genetic algorithm is further engaged to discover the optimal BN in the case of population variation.	3.83	Coastal hazards

[a] Average Citations per Year (note: the source is WoS by the end of February 2023).

resilience solutions. The lack of deep study on sustainable system resilience, its characteristics, and interdependency asserts that organizational practices may lead to infeasible outcomes in system resilience. Besides, it is prone to vulnerability increase in the collapse of both industrial and social-ecological sectors.

The leading sustainable resilience characteristics contributing to the CE throughout e-waste operation management are identified in this regard. The resilience characteristics are then validated by reviewing the existing literature, interviewing with the infield subject-matter experts (SMEs), and to the best of authors' understanding. Moreover, the causality and relationships among the sustainable resilience characteristics are also examined using the proposed framework in the context of dynamic BN and an advanced fuzzy set theory. Keeping in mind the superiority of the dynamic BN technique compared to the other structural causal dependency decision-making tools like Fuzzy Cognitive Map (FCM) [46–48], Interpretive Structural Modeling (ISM) [49,50], and Decision-Making Trail and Evaluation Laboratory (DEMATEL) [51,52], dynamic BN is applied to examine the causes and effects of sustainable and resilient e-waste operation management. As a result, policymakers are able to implement, promote, and update the current practical strategic plans for sustainable resilience in e-waste operation management. It should be noted that the objective of this study is not necessarily to assess the potential disruptions in London. Rather, it is to shed light on the most vulnerable contributing factors for creating sustainable resilience in e-waste operation management over time.

In the e-waste management and the overarching framework of the CE, a critical need arises to bridge existing gaps in research and operational necessities. This imperative stems from the complexity of modern e-waste challenges and the transformative potential of CE principles. Our study seizes the opportunity to fill these gaps and advance the frontiers of knowledge in sustainable resilience within the domain of e-waste operation management, with a specific focus on the consolidating perspective of the CE. By conducting a thorough review of the existing literature and pinpointing critical research gaps, our research makes a distinctive contribution to the field. It goes beyond mere theoretical exploration to offer practical insights and solutions for the efficient and effective operation of sustainable, resilient e-waste management systems. Notably, our study directly addresses the pressing concerns of London Metropolitan city's ambitious aim to achieve zero-carbon status by the year 2050, aligning with global sustainability goals.

The significance of our current endeavor extends across a wide spectrum of prospects. We explore the intricate interplay between e-waste management and the CE, shedding light on innovative strategies that can be employed to achieve both environmental sustainability and economic growth. As the contemporary literature on e-waste management continues to grow, our research stands out with its distinct research objectives and contributions.

In this context, to define the sustainable resilience characteristics for e-waste operation management:

- Framework Development: We pioneer the development of a comprehensive framework for sustainable, resilient e-waste operation management within the CE paradigm. This framework not only offers a theoretical foundation but also provides actionable guidance for practitioners and policymakers.
- Case Study Application: Our study selected London Metropolitan City as the subject of our case study due to its unique characteristics that align with the core principles of the CE, e-waste management, and system resilience. We will not only elucidate the specific features of London that make it a relevant and insightful case but also demonstrate how our proposed framework can be effectively translated into actionable strategies for e-waste management within this context. By choosing London, we aim to provide a tangible and practical illustration of how CE principles can be applied to address e-waste management challenges while enhancing system resilience in a real-world urban environment. This choice is grounded in London's commitment to sustainability, its diverse urban population, and its dynamic e-waste landscape, making it an ideal setting to showcase the intersection of theory and practice in the context of CE principles and e-waste management.
- Resilience Assessment: We introduce novel resilience assessment methodologies, grounded in BN modeling, to evaluate the adaptability and responsiveness of e-waste management systems. This innovative approach empowers decision-makers with a deeper understanding of system dynamics and vulnerabilities.
- Policy Implications: We offer practical policy recommendations that emerge from our findings, guiding policymakers on how to align e-waste management practices with broader sustainability goals, including carbon neutrality.

Our research transcends the boundaries of conventional e-waste management studies by not only addressing the urgent sustainability challenges but also by providing tangible solutions. It contributes to the evolving discourse on resilient e-waste operation management within the CE, offering a roadmap for cities and regions striving to balance economic growth with environmental responsibility.

The current research work is organized as follows. Section 2 explains the Materials and Methods for integrating BN into resilience. Section 3 uses the e-waste management system of London as an example to illustrate the usefulness and versatility of the proposed approach in terms of Results and Discussion. Section 4 provides implications and recommendations for future research prospects. Finally, the conclusion of this study highlights the challenges, observations, and suggestions for further research.

2. Materials and Methods

2.1. Proposed framework

This section develops a framework to dynamically assess and evaluate the sustainable resilience of e-waste operation management in complex systems. In the traditional e-waste operation management approach, the operation management in a complex system would be further improved once a disruption occurs. E-waste operation management is a multi-dimensional discipline in complex business practice. Hence, assessing and evaluating resilience regarding operation management is much desired and needed. In this regard, the impact of potential disruptions on system operation management must be appropriately understood and operations must be capable of developing an early response before facing any consequences. Fig. 3 illustrates a key five-step framework to quantify the resilience of e-waste operation management. The feasibility of data needs to be assessed, or any data mining required should be carried out in this step. Step two describes the sustainable resilience characteristics of e-waste operation management underlying the resilience index (RI) definition for quantification purposes. Step three determines the causality between the resilience characteristics (i.e., disruption, absorption, adaptation, and recovery), and the relevant influential diagram is drafted accordingly. At this stage, if there is sufficient information, we could proceed. If not, we return to step one. Step four constructs the structure of the BN model and provides all feeds with all required input data. The input data can be derived objectively using historical data or subjectively through the expert judgment elicitation process.

It should be noted that uncertainty handling for the input data is out of the scope of the present work because it has been widely discussed in previous authors' research studies, including the use of advanced probabilistic methods or an extension of progressive fuzzy set theories [53–55]. In step five, the sustainable resilience of e-waste operation management is assessed through four types of analysis: 1) forward propagation, 2) backward propagation, 3) information theory, and 4) sensitivity analysis. The results are valid since new evidence becomes available and should go back to step 4 b y further developing the dynamic BN and continuing to proceed.

The details of each step are explained as follows.

Step One: Defining the system & collecting all required information

To define our understudy system, it is necessary to specify and have an insight at least into its components, boundaries, inputs, processes, and outputs by answering some questions, such as: What are the parts that make up the system? What are the limits or boundaries of the system? What are the processes or functions that the system performs? What are the inputs or resources required by the system for it to function? And what are the outputs or outcomes produced by the system?

The required data in terms of e-waste operation management would be gathered from varied sources, including but not limited to

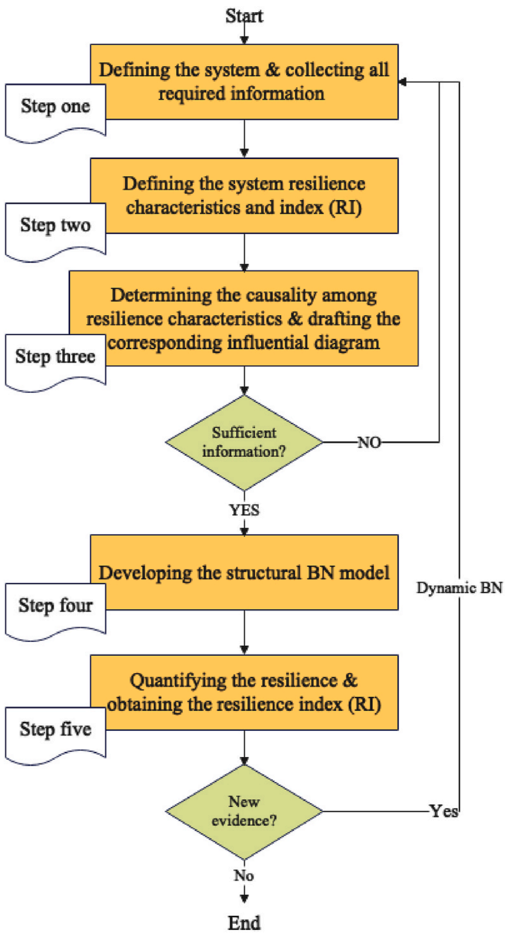

Fig. 3. The developed framework for sustainable resilient e-waste operation management.

official published reports, operational conditions, state-of-the-art, and interviews with well-recognized SMEs. In addition, a group of SMEs underlying the context of the Drexler/Sibbett team process aimed to collaborate in this resilience assessment method incorporating visual thinking and graphic facilitation techniques. The team began by researching to gather information and insights on the project or problem. The team then created visual maps or diagrams to help them make sense of the information they have collected. The team aggregated their opinions and the outcome was used for the next step. In addition, this step gathers a heterogeneous group of nationally and internationally recognized 15 SMEs with experience in e-waste operation management underlying the context of the Drexler/Sibbett team process [56]. The SMEs have different education levels (five BSc, five MSc, and five Ph.D.), diverse genders (six male, seven females, two LGBTQ), a wide range of tenure experiences (five with less than 10 years, five with between 10 and 15 years, and five with more than 15 years). However, considering previous authors' reference works [57,58] and a bit high quantity of employed SMEs, this study assumes that the importance of weights of all SMEs are equal and their importance weighs differences is negligible. A sample questionnaire on how SMEs provide information, and their contributions, can be provided upon official request to the corresponding author.

Step Two: Defining the system resilience characteristics and index (RI)

Over the last few years, certain studies have attempted to quantify the resilience of critical infrastructure. For example, robustness, resourcefulness, rapid recovery, and adaptability are considered four main dimensions of resilience in a study conducted by Bruneau et al. [59]. In that study, resilience is quantified as a functionality loss by assuming full system reliability minus the system quality after disruption over time.

The concept of dynamic resilience is defined in the study of Rose [60] based on time-dependent recoverability. In another time-dependent approach [61], resilience is counted as the system performance recoverability and loss ratio.

Several other approaches have been developed for resilience quantification purposes, including but not limited to fuzzy set theory [62], probabilistic (e.g., BN) [63,64], deterministic [65,66], conceptual [67,68], simulation [69,70], mathematical formulations [71–73], among others.

Fig. 4 depicts the performance functionality (PF) of a typical system over time. In the system safety and reliability concept, system reliability reduces reaching failure points. In the event of an unforeseen circumstance, the ability of the system to withstand and recover from the incident demonstrates its level of resilience and exposes potential areas for process improvement. Once disruption occurs, the system vulnerability plays an important role, which in this study is the absorption resilience characteristic. Then, the recoverability of PF is engaged as a combination of adaptation and recovery resilience characteristics. In the current work, we define the RI probabilistically for quantification, in which RI indicates resilience rate in the interval of [0, 1]. In a partial resilience assessment, RI is defined as a metric for measuring the system resilience over time as the summation of system reliability given the disruption and resilience characteristics (absorption, adaptation, and restoration). The learning characteristic might also be added here. This explanation can be transferred into a simplified mathematical formulation as follows:

$$\overline{RI} = PF(Reliability|Disruption) + PF(Absorption) + PF(Adaptation) + PF(Restoration) + \{PF(Learning)\} \quad (1)$$

Step Three: Determining the causality among resilience characteristics & drafting the corresponding influential diagram

This is a straightforward step as well as the most critical step in sustainable resilient e-waste operation management. Determining the causality among resilience characteristics involves identifying the relationships between different characteristics and determining which characteristics have a causal impact on others. To create a corresponding influential diagram, it is necessary to map out these relationships and show the direction of the causal relationships.

Fig. 5 illustrates an example of an influential diagram for resilience characteristics. As can be seen, the RI is located at the center, with arrows pointing toward it from four plus one characteristics: 1) reliability|disruption, 2) adaptability, 3) absorbability, 4) storability, and 5) learning ability. This figure indicates that these characteristics have a causal impact on the RI. Each characteristic needs

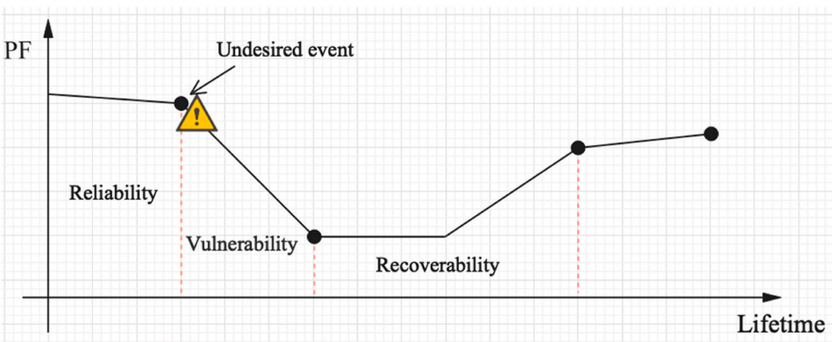

Fig. 4. A typical system performance functionality over the system's lifetime.

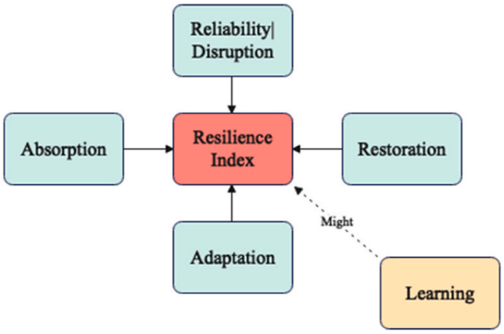

Fig. 5. Causality determination among the resilience characteristics.

to go further and be analyzed in depth to gain a more realistic outcome for the system's resilience. This in-depth analysis makes this step critical in the sustainable resilience framework. To the analyze "adaptability" characteristic in depth, one can consider the following questions.

- What changes or challenges (e.g., technology, market conditions, and social or political dynamics) is the system likely to face, and how might they impact the system?
- How does the system's organizational structure or governance model facilitate or inhibit "adaptability"? For example, a system might have a decentralized decision-making structure allowing for flexibility and quick response to changes, or it might be highly centralized and hierarchical, which may inhibit "adaptability."
- How does the system's culture or values influence "adaptability"? For example, cultural norms about risk-taking, innovation, or change affect the system's capability for adaptability.
- How do external factors (e.g., access to resources or social support) influence "adaptability"?
- How can the system build its capacity for "adaptability"? Can the system invest in training or development programs to increase skills or capacity for innovation, or can it engage in regular strategic planning to predict and respond to environmental changes?

Answering these questions and analyzing "adaptability" in depth can further develop it using input data objectively or subjectively. Finally, the RI can determine this resilience characteristic's contribution. The exact process needs to be applied to the rest of the resilience characteristics in practice.

Step Four: Developing the structural BN model

In this step, the structure of the BN model as a powerful decision-making tool, especially in the uncertain and stochastic environmental condition of the complex system, is developed. The BN model can conduct a reliable inference rationally, in which the prior belief of every single element will be updated. The prior beliefs (in this study, the rate value) are commonly allocated using historical data or by engaging the expert judgment elicitation process. BN assists decision-makers in addressing the causality of relationships (arcs) among the set of interacting nodes (variables) [74]. The structure of BN indicates a comprehensive joint probability distribution (JPD), where the following two relations are identical: "cause → effect" and "cause ← effect." The Bayes rule should be applied to construct the BN model, where the probability (P) that both elements A and B occur is the probability production of A and B were given A. This mathematically can be presented as equation (2):

$$P(A \cap B) = P(A) \times P(B|A) \tag{2}$$

Considering the symmetry rule, the mentioned equation can be rewritten as equation (3):

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{3}$$

Let us assume that there would be n variables, such as $Y_1, Y_2, Y_3, \ldots, Y_n$. The JPD of constructed BN model can be presented as the following as equation (4):

$$P(Y_1, Y_2, Y_3, \ldots, Y_n) = P(Y_1|Y_2, Y_3, \ldots, Y_n)\ P(Y_2|Y_3, \ldots, Y_n)\ldots P(Y_{n-1}|P_n)P(Y_n) \tag{4}$$

The simplified version of the equation, as mentioned above, can be presented as equation (5):

$$P(Y_1, Y_2, Y_3, \ldots, Y_n) = \prod_{i=1}^{n} P(Y_i|Y_{i+1}, Y_{i+2}, \ldots, Y_n) = \prod_{i=1}^{n} P(Y_i|Parents(Y_i)) \tag{5}$$

This step demonstrates the causality among resilience characteristics in the London Metropolitan city case study as a function of the diverse contributing factors. GeNIe Modeler software (https://www.bayesfusion.com/genie/) was used to draw the influential diagram and will further be used for resilience quantification and assessment.

Step Five: Quantifying the resilience & obtaining the resilience index (RI)

In this critical step, we acquire the RI at the highest hierarchy level within the influential diagram through precise mathematical formulations within the BN model. Furthermore, we undertake a comprehensive evaluation of the sustainable resilience of e-waste operation management by employing a suite of analytical techniques, including forward and backward propagation, information theory, and sensitivity analysis. It is worth noting that additional details regarding the application and outcomes of the four analyses (forward propagation, backward propagation, information theory, and sensitivity analysis) are essential for a complete understanding of our methodology. However, we have relegated this supplementary information to a separate section to maintain clarity and conciseness in this section. The forthcoming results and outputs will elucidate how each of these analytical tools was harnessed to assess the sustainability and resilience of e-waste operation management.

- Forward propagation:

The variables' posterior probability is computed during the probabilistic inference analysis of the BN structural model. As the flow of information is not rigidly directed, this analysis can be performed on every single node in the model, making it a powerful tool for assessing the impact of various factors on a system's resilience. Forward propagation is a type of propagation analysis that is a set of observed or individual variables that measures the relevant impact on the targeted node.

- Backward propagation:

Backward propagation enables BN to determine and compute the variations of the posterior distribution concerning the network parameters. BN can also calculate the MDs of forerunner variables, in which the impact of a specified variable is propagated in backward propagation analysis through the whole of the network.

- Information theory:
- The information theory proposed by Shannon and Weaver [75] is used to enhance the computation quality in the network. Entropy is an essential parameter when using this method to compute the mutual information among parental and child nodes. Assuming that $P(X)$ and $H(X)$ indicate the random variable X probability and entropy, respectively, and considering the concept of risk and resilience, entropy can be used for uncertainty measurement and can be derived as:

$$H(X) = -\sum_{x\in X} P_x(x) log_2 P_x(x) \tag{6}$$

Assuming that the targeted node X entropy is conditional on the corresponding dependent variable Y, then the relationship can be presented as the following:

$$H(Y|X) = \sum_{i} P(Y_i) H(Y_i|X_i) \tag{7}$$

In which i refers to the states' number. In addition, the mutual information among the two targeted nodes and the corresponding conditional node can be obtained as:

$$I(X, Y) = H(X) - H(Y|X) \tag{8}$$

In which $I(X, Y)$ demonstrates the mutual information among the targeted node and the corresponding dependent node, $H(X)$ refers to the targeted node marginal entropy, and $H(Y|X)$ signifies targeted node conditional entropy on the corresponding dependent node.

- Sensitivity analysis:

Sensitivity analysis (SA) is a powerful approach to validate the PERT-built simulation model. SA in BN can provide a graphical illustration for understanding the most significant impact of a set of variable nodes on a targeted node. There are several techniques used for SA in BN, including one-factor-at-a-time (OFAT) analysis, variance-based methods such as Sobol's indices, and global sensitivity analysis (GSA) methods such as Monte Carlo simulation and Latin hypercube sampling.

The next section studies a case study of London Metropolitan city for developing sustainable resilient e-waste operation management.

3. Results and Discussion

The UK is one of the world's most extensive e-waste materials producers (almost 24 kg per person) [76]. For example, the UK produced approximately 150,000 tons between January 2021 and June 2021, an amount that is equal to the weight of 15 Eiffel Towers. Thus, e-waste operation management has become top priority for the UK. According to the field research, the London Metropolitan city faces several challenges in e-waste operation management, including but not limited to regulatory compliance, financial constraints, recycling capacity, collection and transportation, and lack of awareness. In this regard, London Metropolitan city has taken a comprehensive approach to e-waste operation management, addressing the challenges through awareness campaigns, collection and transportation, recycling capacity, financial support, regulatory compliance, consumer education, and public-private collaboration. These efforts have helped make London Metropolitan city a potential leading sustainable, zero-carbon city by 2050. However, as a complex system, London Metropolitan city needs to manage e-waste operations sustainably and resiliently over time.

This study helps policymakers gain broad and viable insights into developing sustainable and resilient e-waste management operations to achieve the city's sustainability objectives.

As mentioned earlier, the London Metropolitan city, as a complex system, is considered to develop sustainable resilience in e-waste operation management in this step. Looking at the city's policies and governmental plans, the following are some of the main existing measures taken to manage e-waste operations in practice.

- Recycling programs: London has well-established recycling programs for e-waste. These programs encourage residents to dispose of their e-waste responsibly and provide a convenient disposal method.
- Extended producer responsibility (EPR): London has properly implemented EPR regulations, making manufacturers responsible for e-waste disposal at the end of the life cycle. EPR regulations have incentivized manufacturers to produce more environmentally friendly products and reduce the amount of e-waste generated.
- Partnership with non-governmental organizations (NGOs): London has partnered with several NGOs specializing in e-waste operation management to enhance sustainability. Such partnerships can provide more comprehensive and effective e-waste operation management program development.
- Landfill bans: London has banned the disposal of certain electronic items in landfills to reduce the amount of e-waste going into landfills.
- Awareness campaigns: London has run several awareness campaigns to educate residents on why e-waste management is a critical concern. Awareness campaigns have helped raise awareness of the issue and encouraged more people to dispose of their e-waste responsibly.
- Certification programs: London has encouraged businesses and organizations to participate in e-waste certification programs such as "Waste electric and electronic equipment (WEEE) certification." These programs guarantee that e-waste is addressed and disposed of in a responsible and environmentally friendly manner.
- E-waste collection points: London has established several e-waste collection points throughout the city, where residents can drop off e-waste for disposal.

In this phase of the study, we aim to establish a RI for the e-waste operation management system based on assessing various resilience characteristics, including absorption, adaptation, recovery, learning, and reliability in the face of potential disruptions. Developing a comprehensive understanding of these resilience characteristics necessitates a holistic approach that encompasses a deep analysis of the system's structure, functionality, behavior, and vulnerabilities, and an exploration of factors that may impact its capacity to withstand and recover from disruptions. The process involves several key steps. Initially, we identify critical functions within the e-waste operation management system and assess potential threats and vulnerabilities it may encounter. Subsequently, we define and delineate resilience characteristics, ensuring a clear and precise understanding of each aspect. This process is rooted in a collaborative effort, where interactive meetings were conducted with the active participation of 15 SMEs. During these sessions, we engaged in a comprehensive review of relevant literature, reports, historical data, and existing documents to inform our understanding of resilience characteristics. To address differences of opinion and ensure a robust analysis, we fostered open discussions and encouraged SMEs to share their insights. Specific questions were posed to guide the exploration of resilience characteristics, including inquiries about the system's past responses to disruptions, its ability to adapt, and the lessons learned from previous incidents. As a culmination of this rigorous process, the findings are shown in Table A, included in Appendix A, which highlights the identified 57 resilience characteristics crucial for a sustainable and resilient e-waste operation management system. Since London —is a complex and multi-dimensional system, the number of resilience characteristics might be more than those defined in this study, which can be considered a restriction of current work.

During the interactive meetings with the 15 SMEs, qualitative and expert knowledge was gathered to inform our research on resilience characteristics in sustainable e-waste operation management. The data extracted from these meetings are categorized into the following key components.

1. **Expert Opinions and Insights:** The SMEs shared their expert opinions and insights regarding the e-waste operation management system's resilience characteristics. These insights encompassed a wide range of topics, including their assessments of the system's strengths and weaknesses, previous responses to disruptions, and perceptions of the system's critical functions.
2. **Historical Data and Case Studies:** As part of the discussions, historical data and real-world case studies were presented and discussed. These data included documented incidents, past disruptions, and strategies to mitigate and recover from these events. The discussions explored into the specific challenges faced and lessons learned from previous incidents.
3. **Documentation Review:** The meetings involved a comprehensive review of relevant literature, reports, and existing documents related to e-waste management and system resilience. This documentation provided valuable background information and context for our analysis.
4. **Resilience Characteristic Identification:** Through collaborative discussions and guided questioning, the SMEs actively contributed to identifying and refining specific resilience characteristics. Questions posed during the meetings revolved around the system's adaptability, capacity to absorb shocks, ability to recover, and its overall reliability. These discussions aimed to clarify and define each characteristic in detail.

5. **Consensus Building:** When differing opinions arose, the meetings were structured to facilitate consensus building. Discrepancies in expert viewpoints were acknowledged and discussed openly, leading to refined definitions and a more comprehensive understanding of resilience characteristics.

Detailed minutes and transcripts of these meetings were recorded to ensure the transparency and reliability of our findings. These records serve as a rich source of qualitative data, capturing the nuanced insights and discussions of the SMEs. The data extracted from these meetings were then synthesized and used to inform the development of the RI and other aspects of our research.

The related meaningful diagram is depicted in Fig. 6 in terms of sustainable resilient e-waste operation management.

Various sorts of nodes, including discrete and continuous, can be designed using the GeNIe Modeler. However, in this study, most of the nodes are constructed continuously. Continuous variables using random probability distributions can take an extended length of time to complete. Given that 15 SMEs are participating in this study, it is preferable to use the probabilistic model rather than shifting to fuzzy set theory, as the confidence level and uncertainty can be measured and would further add value to the validity of the work. After collecting all the necessary information from the group of SMEs, the corresponding truncated normal distribution is set, taking into account the mean, variance, lower bound, and upper bound, represented as (TruncNormal (mu, sigma, lower, [upper])).

TruncNormal is a simplified version of the normal distribution that determines the mean values within a specified lower and upper bound interval. It is one of the feasible and potential ways to present continuous variables in a sustainable e-waste operation management system, except in cases where the normal distribution may not be appropriate due to the presence of outliers or other non-normal features in the data.

In addition, some ordinal discrete variables take on a countable number of distinct values and are defined with three states (low, moderate, and high). The ordinal discrete variables make them easier to work with mathematically and computationally, as they can be easily represented and manipulated using discrete probability distributions.

As mentioned, all input parameters for TruncNormal distribution and discrete variables are generated by collecting and analyzing the expert's judgment elicitation process.

As discussed earlier, 57 contributing factors in resilience characteristics were identified as contributing to disruption, absorption, adaptation, recovery, and learning of e-waste operation management. First, the prior probability of disruption, absorption, adaptation, and restoration are represented as TruncNormal distributions and expressions based on experts' elicitation procedure. In other words, these disruption, absorption, adaptation, and recovery variables follow the same rules of TruncNormal distribution variables. The posterior probability distribution for the RI as a part of forward propagation analysis is computed based on equation (1) (weighted/average sum of the rate of its parental nodes). Fig. 7 depicts the structural BN model without considering the learning resilience characteristics. As a result, the mean value of RI is derived as 0.5606, with the StdDev 0.01342. Fig. 8 illustrates the PDF (probability density function) and CDF (cumulative density function) of RI in BN model analysis according to the Kurtosis variation from 2 to 5, indicating the RI value is identical. In addition, Fig. 9 shows the structural BN model, considering the learning resilience

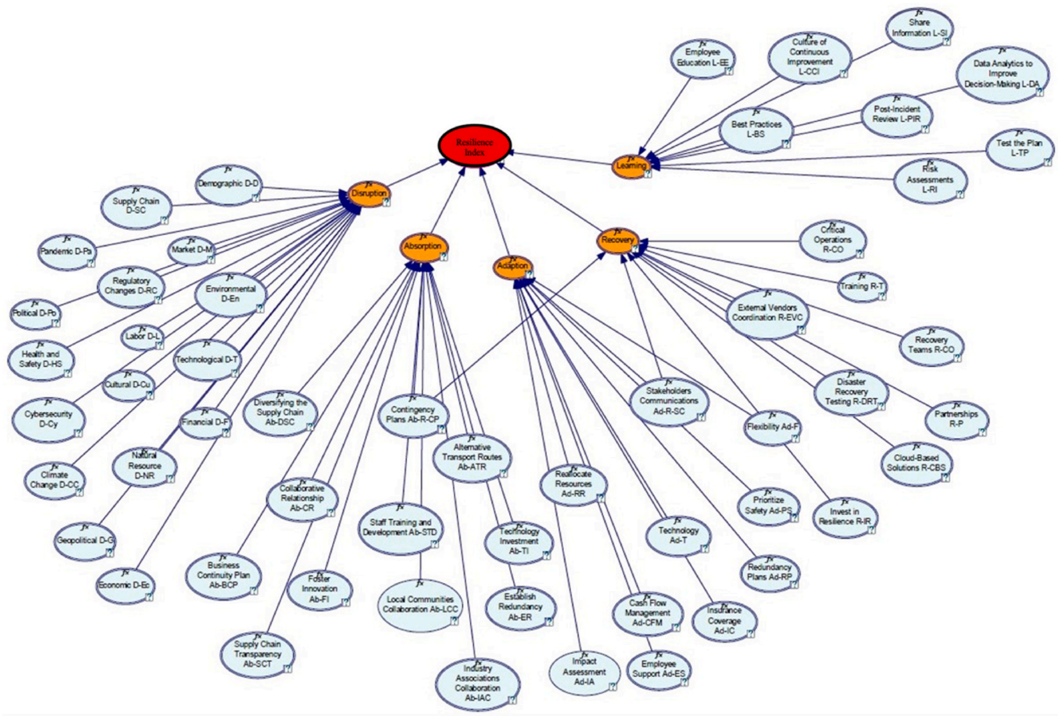

Fig. 6. The influential diagram of sustainable resilient e-waste operation management.

characteristics. As a result, the mean value of RI is derived as 0.5424, with the StdDev 0.01350. Similarly, the PDF and CDF of RI in BN model analysis according to the Kurtosis variation from 2 to 5 are demonstrated in Fig. 10. This outcome confirms our understanding that, similar to system reliability, resilience might also be reduced over time and would require decision-makers' careful attention in the sustainability development areas.

In this step, first, a dynamic BN model is developed to obtain the sustainable resilience of the e-waste operation management for an identified period. The structural dynamic BN within the 30-slice time frame is displayed in Fig. 11. In this assessment, it is assumed that the time slice is based on the year. The outcomes indicate that the resilience characteristics at time $t = 0$ are disruption 0.4218, absorption 0.3782, adaptation 0.5194, and restoration 0.4375. Following that, to assess the resilience between time slices 1 and 30, the node disruption is set to 1 as a part of the backward analysis. Fig. 12 demonstrates that the sustainable resilience of the e-waste operation management system decreases slowly, reaching the lowest point of 0.0809 at $t = 7$. From the obtained results, it can be concluded that the 90 % restoration PF loss from the lowest point is equal to 0.9080 (i.e., $0.90 \times (1–0.0809) + 0.0809$) in 15 time slices (i.e., $22–7 = 15$).

Moreover, in a sustainable and resilient e-waste operation management system, having a lower absorption value resulted in more PF loss reduction and vice versa. Besides, the resilience characteristics of adaptation and restoration were recovered so that the PF rate stabilized afterward at around 91 %. One of the key observations is that the sustainable resilience of the e-waste operation management system continued to improve PF even after 90 % restoration and stabilized at time $t = 22$.

The first attempt of SA is varying the resilience characteristics, in which the time to 90 % recovery is examined. As shown in Fig. 13, the outcome reveals that the resilience disruption characteristic in existing situations has the highest variation among the rest of the resilience characteristics. In addition, the rest of the resilience characteristics are steady state to some point over time.

In the second SA performance, the learning node is added to the dynamic BN model, which has only a connection and dependency to the three resilience characteristics (i.e., absorption, adaptation, and restoration), as illustrated in Fig. 14. The node's value is then set as 0.6, 0.75, and 0.90. The outcomes of the sustainable resilience of the system are determined and depicted in Fig. 15. It is evident that e-waste operation management systems with a higher value of learning characteristics rate have a more excellent recovery value. This means that the PF of the system with a more excellent value of learning could be improved rather than one with a lower value of learning. It is vital to note that the experiences that the sustainable resilience of e-waste operation management system learned from the past assist policymakers in improving the corresponding resilience characteristics and further minimize the undesired event in the future. Besides, the system's learning characteristics provide a robust, constructive response based on the knowledge acquired from the undesired events. The system generates comprehensive registry knowledge to better respond to undesired events. The newly obtained knowledge could then be carried out to provide intervention actions and help the field SMEs predict undesired events and make reasonable adjustments in the subsea pipeline.

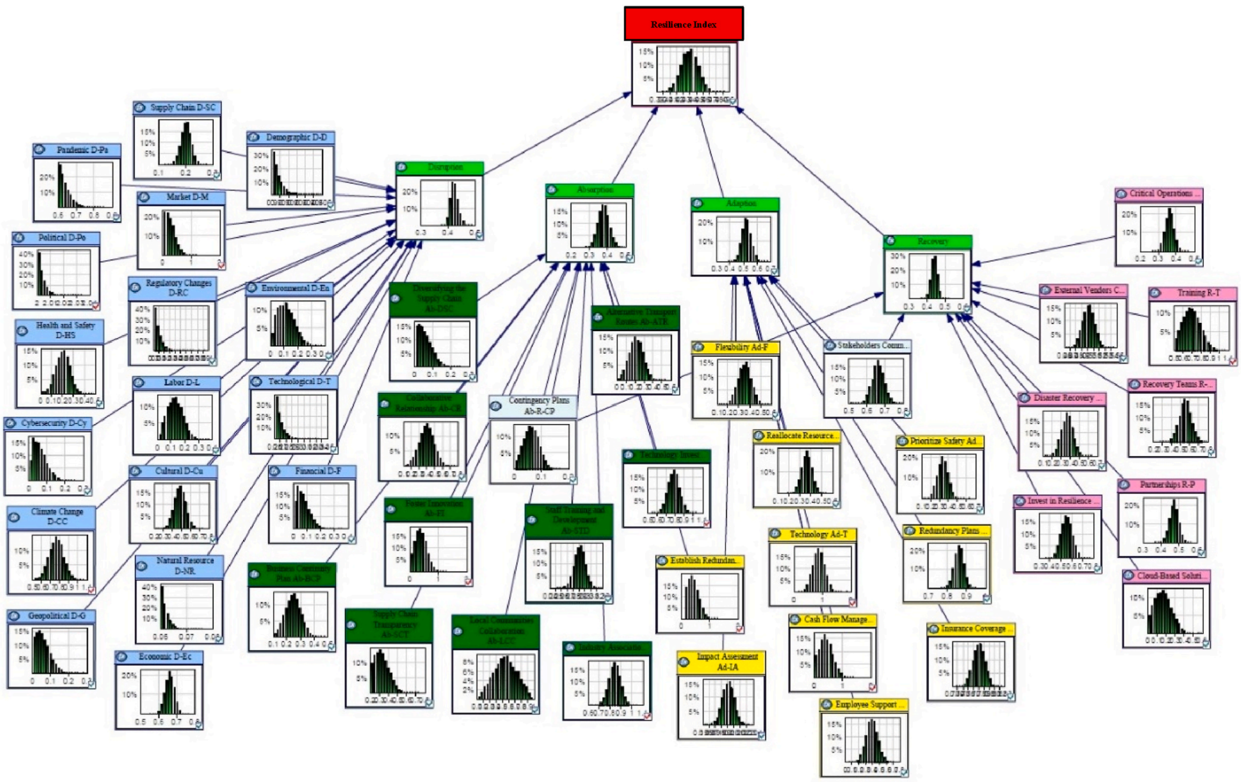

Fig. 7. The structural BN model, without considering the learning resilience characteristics.

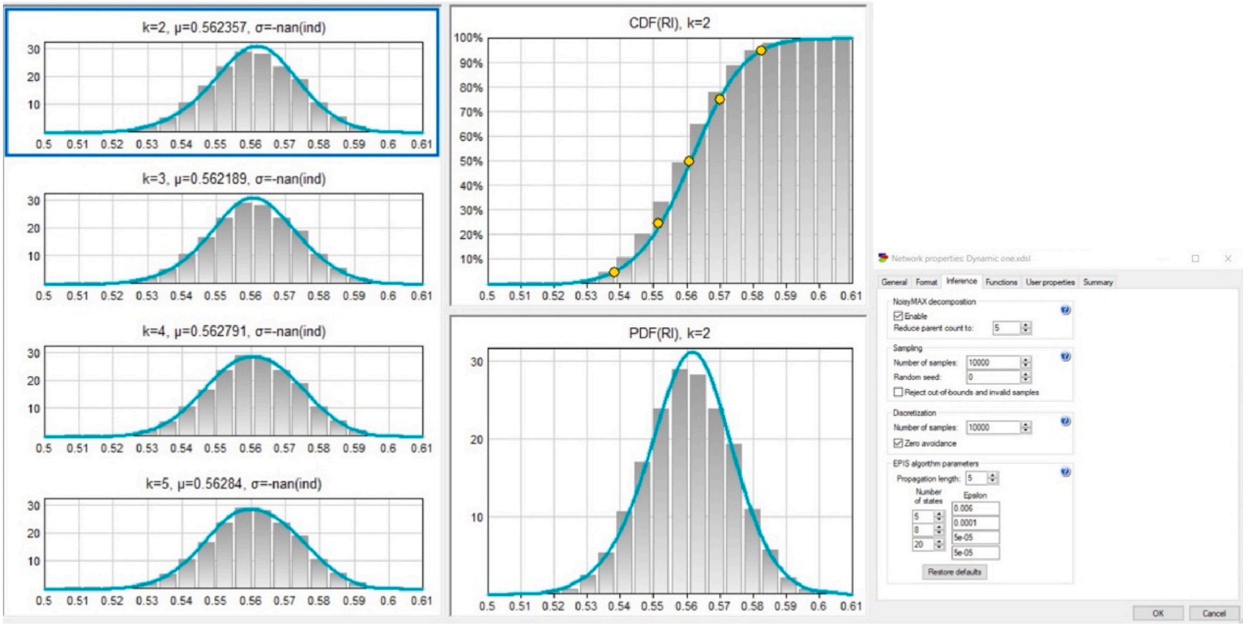

Fig. 8. The PDF and CDF of RI in the structural BN model without considering the learning resilience characteristics, and the corresponding RI network computation properties (Note that: labelled panels no needed).

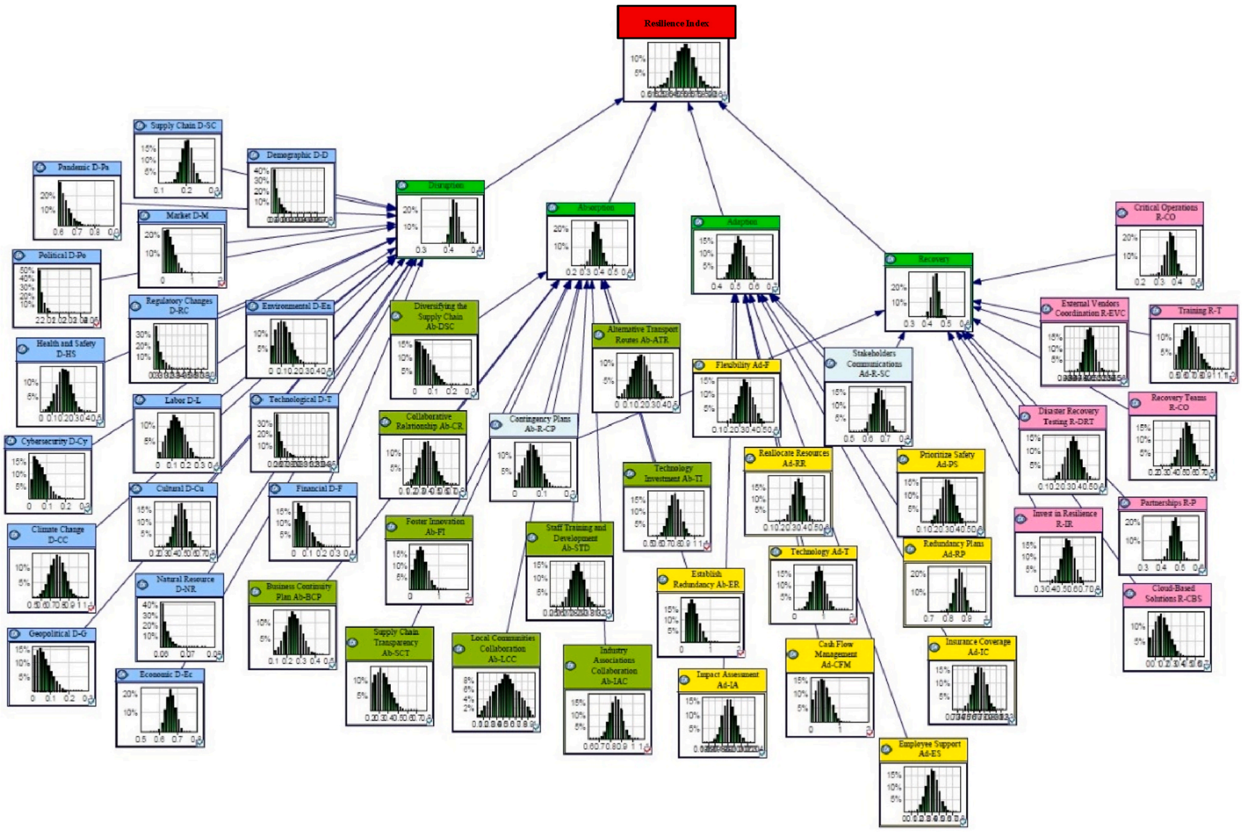

Fig. 9. The structural BN model with consideration of the learning resilience characteristics (Note that: labelled panels no needed).

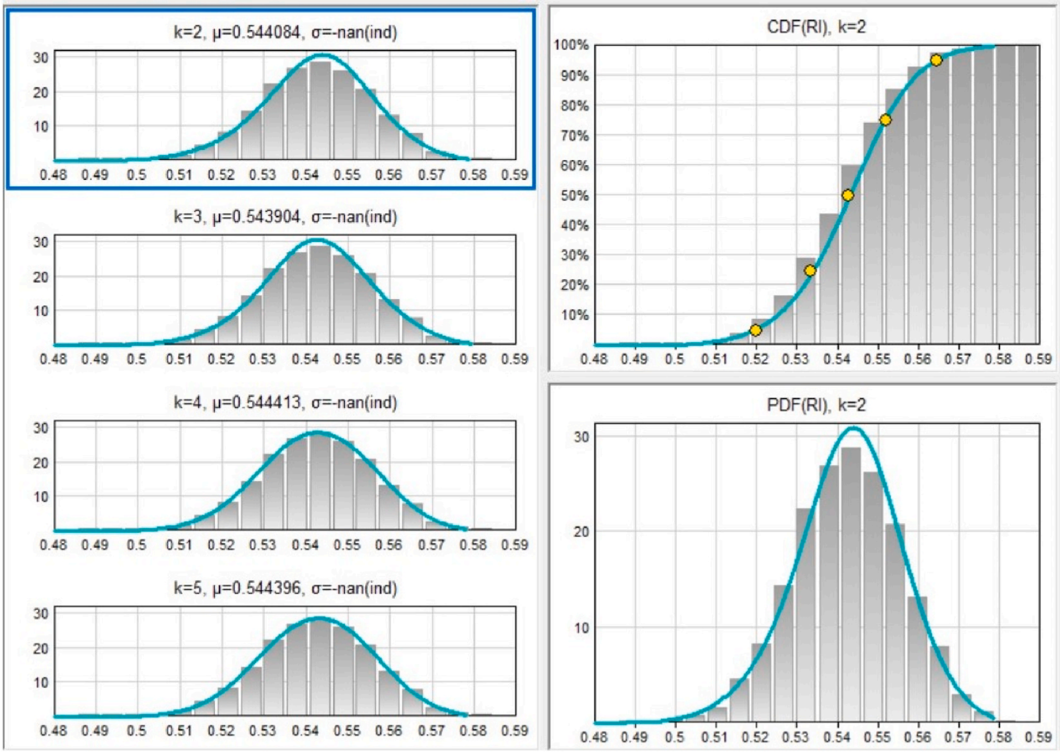

Fig. 10. The PDF and CDF of RI in the structural BN model with consideration of the learning resilience characteristics (Note that: labelled panels no needed).

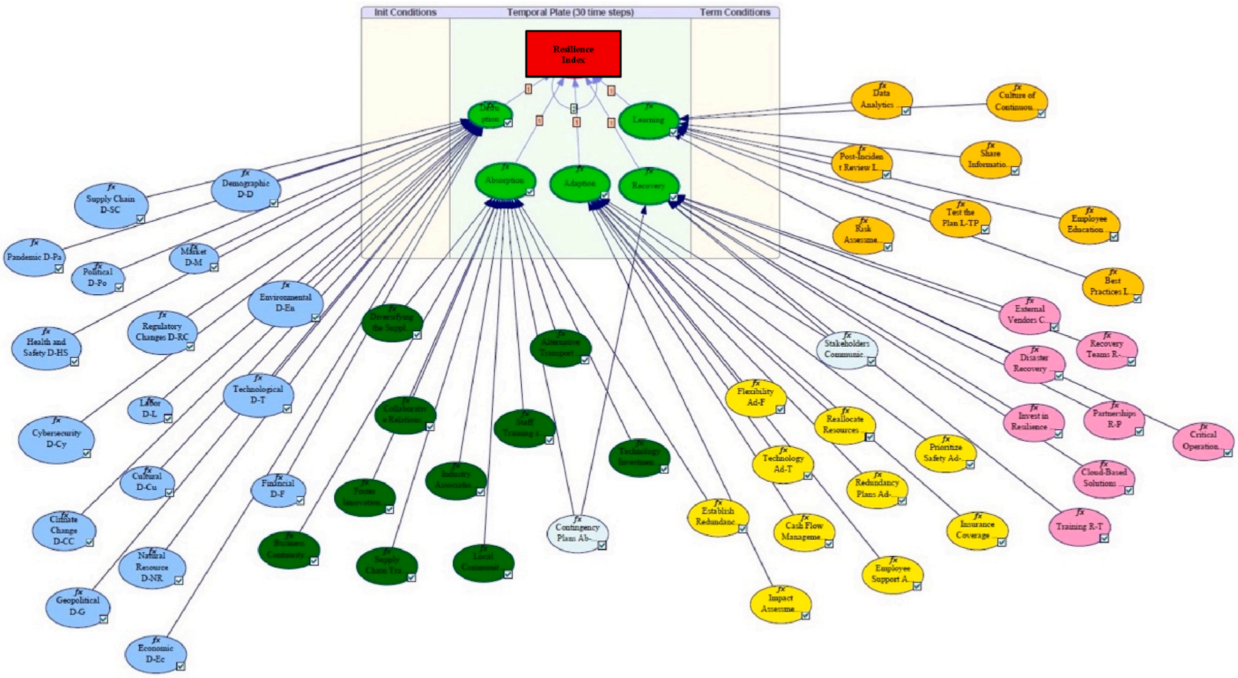

Fig. 11. The dynamic BN for assessing sustainable resilience of the e-waste operation management in an identified period.

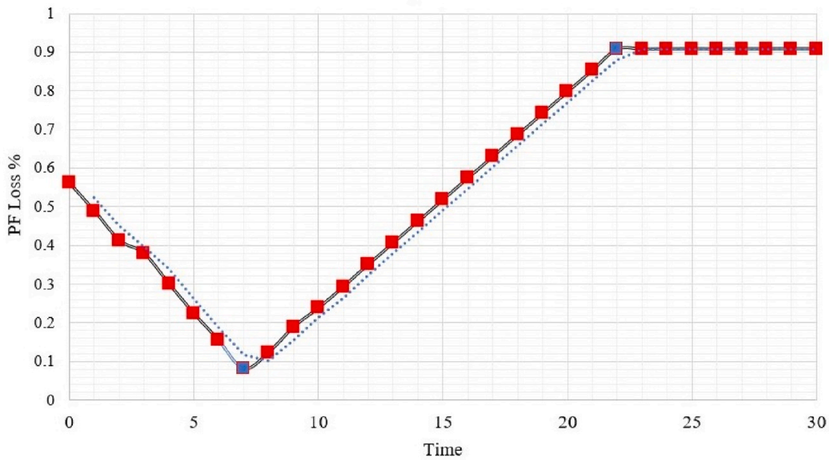

Fig. 12. The sustainable resilience of the e-waste operation management in an identified period.

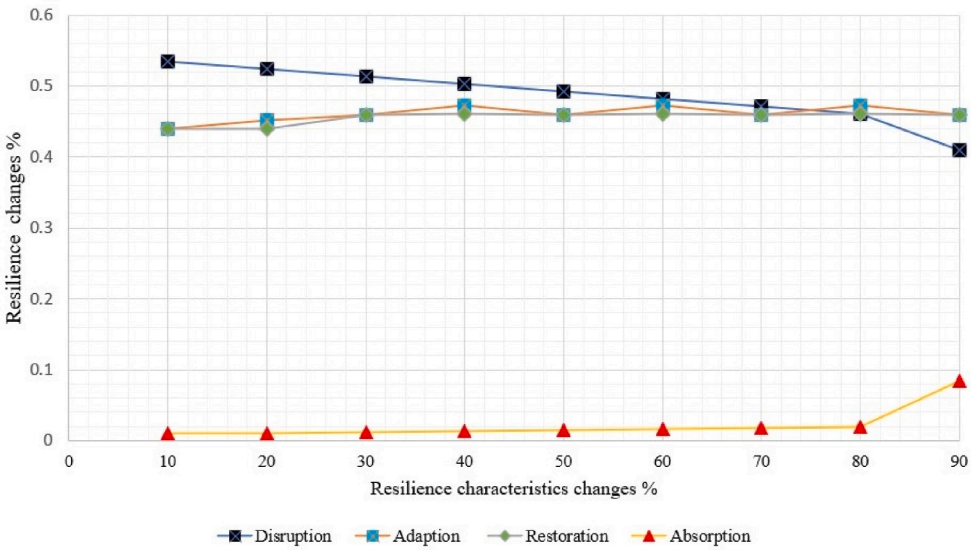

Fig. 13. The SA analysis based on the variation of resilience characteristics on sustainable resilience of e-waste operation management system changes.

In the following resilience quantification assessment, the information theory is conducted in which resilience is conditioned on three characteristics: absorption, adaptation, and restoration. In information theory, we are interested in examining and computing the mutual information between RI and all the resilience characteristics, as mentioned earlier. In order to conduct this assessment, first of all, we convert the equation-based node in the GeNIe Modeler into the discrete-based one with two states, FALSE and TRUE. After that, the computations performed and details are provided as the following. It should be added that $H(RI), H(RI|Absorption)$, and $I(RI|Absorption)$ are computed using equations (6)–(8).

Fig. 16 shows the prior probability of nodes $(RI = TRUE) = 0.659$ and $(RI = FALSE) = 0.341$. Thus, $H(RI)$ *and* $H(RI|Absorption)$ can be calculated as:

$$H(RI) = \sum_{x \in X} P_x(RI)_{log_2} P_x(RI) = -\{0.659\ log_2(0.659) + 0.341\ log_2(0.341)\} = 0.9257$$

and.

$H(RI|Absorption) = \sum_{i=1}^{2} P(RI) \times H(RI|Absorption) = P(RI = TRUE)H(RI = TRUE|Absorption = TRUE) + P(RI = FALSE)H(RI = FALSE|Absorption = NO)$, in which for the computation, the absorption characteristics are set to be TRUE and FALSE respectively in the equation, the BN model is simulated, and the results are provided as follows:

$$H(RI = TRUE|Absorption = TRUE) = -\{0.874\ log_2(0.874) + 0.126\ log_2(0.126)\} = 0.5463$$

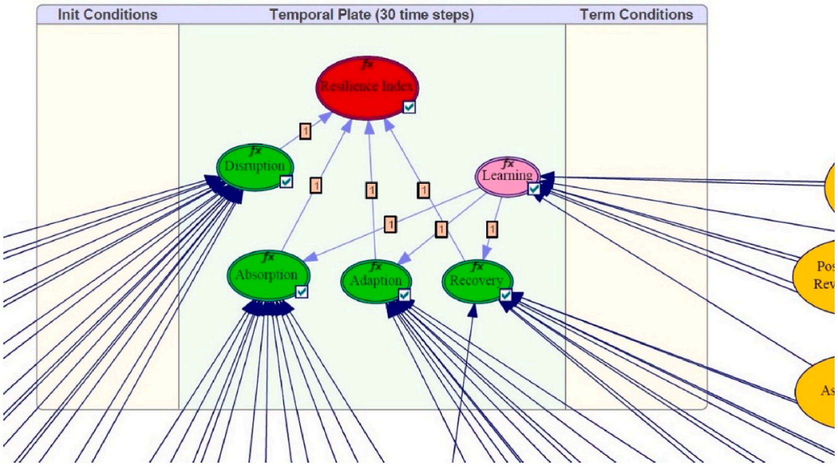

Fig. 14. The SA analysis merely considers the dependency between the learning node and absorption, adaptation, and restoration to the dynamic BN model.

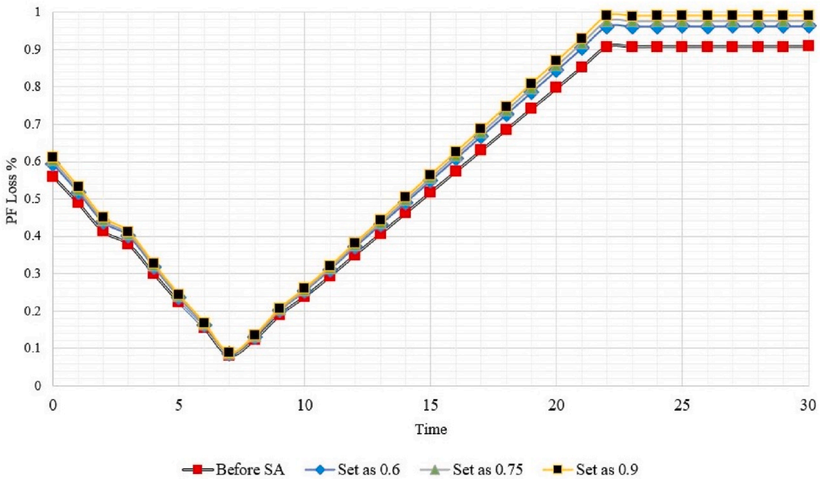

Fig. 15. The SA analysis based on the variation of resilience characteristics with consideration of learning node over time.

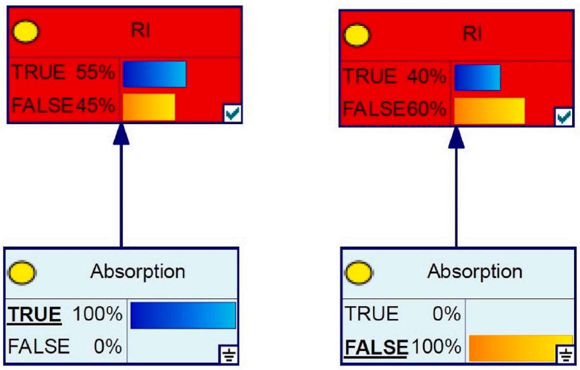

Fig. 16. The state of information theory between IR and absorption characteristic.

$$H(RI = FALSE|Absorption = FALSE) = -\{0.270\ log_2(0.270) + 0.730\ log_2(0.730)\} = 0.8414$$

$$H(RI|Absorption) = (0.659 \times 0.5463) + (0.341 \times 0.8414) = 0.6469$$

$$I(RI|Absorption) = 0.9257 - 0.6469 = 0.2787$$

The results indicate that if the assessors (e.g., policymakers) have proper knowledge regarding absorption resilience characteristics, the uncertainty about the sustainable resilience of the e-waste operation management system can be reduced by 28 %. The summary of results based on information theory analysis is presented in Table 2. It can be concluded that $I(RI|Absorption) \succ I(RI|Adaptation) \succ I(RI|Restoration)$, implying that the absorption resilience characteristics of the e-waste operation management system are the first dense line and have more impact on the uncertainty of the e-waste operation management system.

The findings from the study demonstrate that when assessors, such as policymakers, possess comprehensive knowledge regarding the absorption resilience characteristics of the e-waste operation management system, a substantial reduction in uncertainty, specifically by 28 %, regarding the sustainability and resilience of the system can be achieved. This reduction in uncertainty is significant as it enhances the decision-making process for effectively managing e-waste operations. These results are summarized in Table 2 through an information theory analysis, revealing that absorption resilience characteristics have the highest influence on reducing uncertainty compared to adaptation and restoration characteristics. This suggests that enhancing absorption resilience should be a priority in bolstering the overall resilience of the e-waste operation management system.

Table 2 provides a breakdown of the information theory results for each resilience characteristic, along with the corresponding remarks.

1. Absorption Resilience (Absorption)
- H(RI|Absorption) = 65 %
- I(RI|Absorption) = 28 %
- Remark: Adequate knowledge about absorption resilience can lead to a 28 % reduction in uncertainty regarding the sustainability of the e-waste operation management system.
2. Adaptation Resilience (Adaptation)
- H(RI|Adaptation) = 57 %
- I(RI|Adaptation) = 22 %
- Remark: Adequate knowledge about adaptation resilience can lead to a 22 % reduction in uncertainty regarding the sustainability of the e-waste operation management system.
3. Restoration Resilience (Restoration)
- H(RI|Restoration) = 54 %
- I(RI|Restoration) = 21 %
- Remark: Adequate knowledge about restoration resilience can lead to a 21 % reduction in uncertainty regarding the sustainability of the e-waste operation management system.

To gain deeper insights into absorption resilience, a criticality analysis was conducted to identify the parameters with the most significant influence and contributions to this capacity. This information is crucial for policymakers as it guides them in improving the system's resilience, particularly its absorption capacity, when faced with unforeseen events.

In the criticality analysis, the state of the absorption node was set as TRUE in the GeNIe Modeler, and the variations in contributing factors to the absorption node were assessed. The results of the criticality analysis, ranked in order of significance, are presented in Fig. 17. It is evident from this analysis that "Ab-SCT" (supply chain transparency) and "Ab-DSC" (diversifying the supply chain) are the two most influential factors contributing to the absorption capacity of the e-waste operation management system.

The study underscores the importance of absorption resilience characteristics and their role in reducing uncertainty in the sustainable management of e-waste operations. Policymakers should prioritize strategies related to supply chain transparency and diversification to enhance absorption capacity and bolster the system's overall resilience in the face of unexpected events.

4. Implications for advancing circular economy and sustainable resilience in E-waste management

In our research, we have talked about the critical resilience characteristics necessary for sustaining e-waste management in the UK context and the contributing factors supporting this resilience. We acknowledge the importance of explicitly integrating CE principles

Table 2
The summary of information theory results.

H(RI|Type of resilience characteristics)	Mutual information	Remarks
H(RI|Absorption) = 65%	I(RI|Absorption) = 28%	By having enough and adequate knowledge, the uncertainty can be reduced about the sustainable resilience of the e-waste operation management system by 28 %
H(RI|Adaptation) = 57%	I(RI|Adaptation) = 22%	By having enough and adequate knowledge, the uncertainty can be reduced about the sustainable resilience of the e-waste operation management system by 22 %
H(RI|Restoration) = 54%	I(RI|Restoration) = 21%	By having enough and adequate knowledge, the uncertainty can be reduced about the sustainable resilience of the e-waste operation management system by 21 %

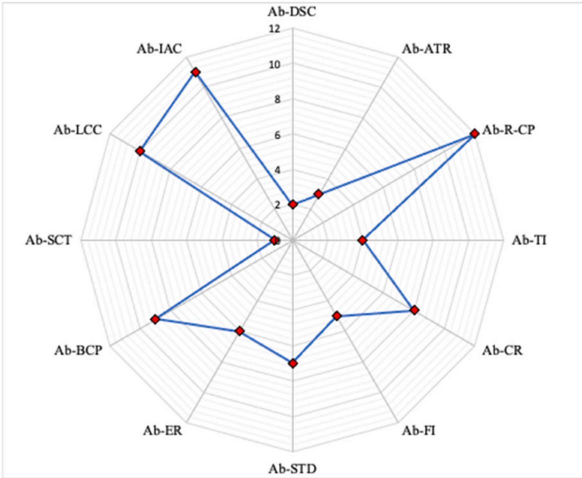

Fig. 17. The criticality analysis in absorption resilience characteristic.

into our discussion, as they fundamentally underpin our findings.

4.1. *Circular economy integration*

The CE framework is integral to our study's focus on sustainable e-waste management. By transitioning from a linear "take-make-dispose" model to a circular one, CE principles emphasize the reduction, reuse, recycling, and responsible disposal of electronic waste. This integration enhances the sustainability and resilience of e-waste operation management in several ways.

- Product Design for Durability and Recycling: CE's emphasis on designing products for durability and ease of recycling aligns with our resilience characteristic of "preparedness for unexpected events." Durable products and easy disassembly for recycling inherently enhance the system's ability to withstand disruptions.
- Collaboration Among Stakeholders: CE practices encourage stakeholders, both public and private, to establish closed-loop systems, fostering collaboration. This resonates with our recommendation for diverse stakeholders to collaborate effectively in tackling complex e-waste challenges.

4.2. *Future directions*

We acknowledge the unconventional placement of future work prospects and will now integrate future directions into our conclusion.

In conclusion, our research underscores the critical connection between CE principles and the sustainable resilience of e-waste management. By embracing CE practices, including product design for durability and recycling and fostering collaboration among stakeholders, we can significantly enhance the resilience of e-waste operation management. Furthermore, our alignment with crucial UN SDGs highlights the broader significance of our findings for achieving sustainability goals.

For future work, we recommend exploring strategies for implementing CE principles in e-waste management and assessing their impact on resilience. Additionally, investigating the role of technology innovation and stakeholder partnerships in achieving sustainable e-waste management remains an important avenue for further research.

Subjectively constructed assessments, such as the one demonstrated in Table B in Appendix, hold significant merit and relevance, especially within the intricate landscape of sustainable development. It is essential to recognize that while scientific methodologies can provide precise quantitative measurements, there are compelling reasons why subjective assessments are necessary and justifiable in evaluating the sustainable resilience of the e-waste operation management system concerning the UN SDGs. These reasons are as follows.

- Complexity and Multifaceted Nature: The UN SDGs embody a web of interconnected, multifaceted objectives that are challenging to distil into purely quantitative metrics. Sustainable development is not solely about numbers; it encompasses qualitative and contextual dimensions influencing outcomes. Subjective assessments offer a means to capture these nuances comprehensively.
- Qualitative and Contextual Understanding: Sustainable development outcomes often hinge on qualitative and context-specific factors that may defy straightforward quantification. Subjective assessments can accommodate these nuances by drawing upon local knowledge, qualitative data, and context-specific insights.

- Holistic Evaluation: The subjective approach enables a more holistic evaluation by considering direct, measurable impacts but also indirect and long-term effects, potential trade-offs, and unintended consequences. It considers the full spectrum of sustainability, promoting a more comprehensive understanding.
- Practicality and Timeliness: While scientific approaches have their place, they can be time-consuming and resource-intensive. Subjective assessments offer practicality and timeliness, making them well-suited for scenarios where swift insights are imperative for decision-making, policy formulation, and advocacy efforts.
- Stakeholder Engagement: Subjective assessments foster stakeholder engagement by incorporating input from diverse voices, including experts, affected communities, and policymakers. This participatory approach enhances consensus-building inclusivity and ensures that the assessment aligns with the values and priorities of those directly impacted.
- Adaptability and Flexibility: Sustainable development is an evolving field, subject to changing dynamics and circumstances. Subjective assessments demonstrate adaptability and flexibility, capable of accommodating emerging knowledge and evolving sustainability priorities.
- Communication and Advocacy: Subjective assessments, often presented in accessible formats such as star ratings or qualitative descriptions, are potent tools for communication. They bridge the gap between complex information and broader audiences, including policymakers and the public, thereby driving awareness and facilitating advocacy efforts.

Nonetheless, it is imperative to balance subjective and scientific assessments. A comprehensive evaluation ideally leverages both approaches, with subjective assessments providing a qualitative narrative and scientific methodologies supplying precise quantitative data. This combined approach ensures a more robust and transparent understanding of the sustainable resilience of e-waste operation management concerning the UN SDGs, enriching the assessment's reliability and credibility. In this manner, the assessment can better inform decision-makers, facilitate informed policy choices, and promote sustainable practices within the e-waste management sector.

5. Conclusion

Many countries and organizations have widely promoted the CE concept in recent years. The UK has been actively facilitating the CE lately, with the government launching its CE package in 2018. The package has been created and targeted by diverse sectors, including policymakers, business communities, and practitioners, within a range of measures designed to encourage businesses and individuals to adopt CE principles sustainably. Thus, to have a sustainable resilient e-waste operation management, it is vital to take a step to transition to a more CE and create new economic opportunities.

Our research into e-waste management and the CE advances these fields' academic and practical understanding and aligns closely with several United Nations SDGs. This alignment is evident in various aspects of our findings and recommendations.

The UK's recent adoption of the CE, marked by the government's launch of its CE package in 2018, is a prime example of an initiative that resonates with the SDGs. This movement towards CE principles in diverse sectors mirrors the objectives outlined in the following vital SDGs.

- Goal 12 Responsible Consumption and Production: Our study underlines the importance of managing e-waste responsibly, a critical aspect of sustainable production and consumption. By promoting the principles of the CE in e-waste management, we contribute directly to achieving this goal.
- Goal 13 Climate Action: The role of technological innovation in e-waste management, as highlighted in our research, contributes significantly to climate change mitigation. This is crucial in addressing the urgent need for climate action.
- Goal 17 Partnerships for the Goals: Our emphasis on collaboration and stakeholder engagement in e-waste management echoes the spirit of Goal 17. The study advocates for global partnerships and multidisciplinary collaboration, which is essential for advancing sustainable e-waste management practices.

In this pioneering research endeavour, we have embarked on the ambitious task of establishing a robust scientific foundation for e-waste operation management within a developed nation, focusing on the key characteristics that drive sustainable resilience. To achieve this, we have employed a dynamic BN framework, chosen for its unique ability to accommodate data and model uncertainties and variability within intricate systems.

In this endeavour, we present a compelling case study that serves as a testament to the efficacy of our proposed framework. This case study centres on the e-waste operation management within the dynamic landscape of London Metropolitan City. It unravels various facets of resilience, shedding light on causal relationships among contributing factors and unveiling interdependencies through influential diagrams.

This research shows that the proposed approach is a promising tool to attract stakeholders to sustainable development work in e-waste management and makes perfect business community sense.

However, it is essential to acknowledge that our study encountered certain challenges that warrant careful consideration in future research endeavours. While we diligently implemented structured processes for gathering and evaluating input from SMEs, we recognize that issues related to bias, lack of transparency, and group dynamics may have influenced the expert judgment elicitation process, particularly in cases involving a more significant number of participating SMEs. These influences could stem from diverse experiences, perspectives, power dynamics, or individual interests among SMEs, impacting their judgments and advice. A proactive approach to managing these issues could include employing multiple data sources to validate expert judgments and developing a hierarchical BN, both of which are explained below.

- Diversify Data Sources: To address potential bias and improve the reliability of expert judgments, we recommend incorporating diverse data sources. This includes utilizing historical data, case studies, and empirical evidence related to e-waste management and system resilience. By triangulating expert opinions with empirical data, we can strengthen the validity of our findings.
- Hierarchical BN: Building on the hierarchical BN approach, we suggest developing a more intricate and fine-grained model that captures the interdependencies among resilience characteristics and their influence on the e-waste operation management system. This approach can provide a systematic framework for quantifying uncertainties and exploring causal relationships among variables. Transparency Framework: To enhance transparency, we propose establishing a comprehensive transparency framework for the expert judgment elicitation process. This framework should include clear documentation of assumptions, criteria for selecting SMEs, and a systematic process for addressing group dynamics. It should also involve regular reviews and audits of the process to identify and rectify any biases. Robust Sensitivity Analysis: Implement a robust sensitivity analysis to assess the impact of variations in expert judgments on the outcomes. This can help identify the most critical variables and areas where uncertainties substantially influence results. Sensitivity analysis can also guide future data collection efforts. Independent Validation: Consider engaging external experts or independent validators who were not part of the original expert meetings to critically evaluate and validate the findings. External validation can provide an unbiased perspective and enhance the credibility of the study's outcomes.

Data availability statement

The data that support the findings of this study are available from the corresponding author, MY, upon reasonable request.

CRediT authorship contribution statement

Rosita Moradi: Writing – original draft, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammad Yazdi:** Writing – review & editing, Writing – original draft, Validation, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Aida Haghighi:** Writing – review & editing, Visualization, Validation, Software, Data curation. **Arman Nedjati:** Writing – review & editing, Visualization, Validation, Resources, Formal analysis, Data curation.

Declaration of competing interest

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e34071.

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