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RISK ANALYSIS AND LIFE CYCLE ASSESSMENT IN ENVIRONMENTAL FORENSICS: PRACTICAL INSTRUCTIONS FOR THEIR USE

Alberto Pivato [1], George Varghese [2], Francesco Di Maria [3], Alessandro Manzardo [1], Massimiliano Lega [4], Maria Cristina Lavagnolo [1], Maria Pettersson [5] and Claire Gwinnett [6]

[1] Department of Civil, Environmental and Architectural Engineering, University of Padova, via Marzolo 9, 35131, Padova, Italy
[2] National Institute of Technology Calicut, Kerala, India
[3] Department of Engineering, Università di Perugia, via G. Duranti 67, 06125 Perugia, Italy
[4] Massimiliano Lega, Napoli Isola C4, 80143, Italy
[5] Department of Business Administration, Technology, Art and Social Sciences, Luleå
[6] Centre for Crime, Justice and Security, Staffordshire University, United Kingdom

1. INTRODUCTION

In the environmental field, we are often faced with problems that are so complex that it is necessary to find methodologies which combine the available information in a manner which allows for effective, logical, transparent and reproducible interpretation which could be qualitative or quantitative. In some cases, there is limited information present or only some information is actually provided; this is the case, for example, of the potential or ongoing environmental impacts associated with a product, process, activity, agent (such as pollutants in different media), or an event (e.g. failure of the bottom liner of a landfill). Risk analysis (RA) and life-cycle assessment (LCA) are the two dominant methods to aid in collating information from these scenarios and enabling decision to be made in the environmental field.

The need to understand the state of the environment in order to make assessments, conclusions and decisions requires elevating the concept of knowledge to that of situational awareness. Situational awareness represents one of the main objectives of any investigative process and, more generally, of environmental forensic engineering and, certainly, LCA and RA represent two valid tools for achieving such goal. In particular, among the most critical aspects of an investigative process is that of revealing the link between causes and effects, both from a logical and physical point of view; LCA and RA relate all elements through logical-conceptual models, supporting the objectification of analysis processes and ensuring the transparency and repeatability of processes by multiple subjects as required by laws and regulations.

Environmental forensic represents an area where the decisions and conclusions have significant financial, legal and social implications. Decisions in environmental forensic cases are normally conducted within the criminal justice framework or equivalent, meaning that they must be transparent and robust. RA and LCA, as previously reported, have these properties and therefore have potential benefits for use in environmental forensics.

The tools of RA and LCA have significant potential for answering key questions posed in environmental forensic scenarios (Ram, 2000), including;

- What was the source of the contamination? Environmental forensic experts may use a combination of analytical and transport modelling techniques to identify from where the chemicals responsible for pollution, came from.
- When did the release occur? With similar techniques as above, environmental forensic experts can assess when the release of uncontrolled pollutants in the environment occurred and how long the event lasted (whether prolonged, short duration or a one-time event). In this context it is important to also understand what historical industry practices and regulatory practices were in place at the time the released occurred and if an insurance coverage was available.
- How did the release occur? Answering this question involves understanding the mechanisms of transport and pathways through which the contaminants were released into the environment. At this stage, it may also be important to analyse the system's reliability, which refers to the ability of a system to consistently perform its intended function over a specified period of time under normal operating conditions (for example the bottom liner of a landfill which prevent the leakage of leachate).
- Who contributed to the problem? In many cases, multiple parties may have contributed to the problem. These may include specific individuals, companies, or government agencies that were involved in activities such as

Managing editors:
Alberto Pivato, Claire Gwinett, George Varghese
email: alberto.pivato@unipd.it, c.gwinnett@staffs.ac.uk, gkv@nitc.ac.in

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industrial operations, waste disposal, or transportation of hazardous materials.

- What is the extent and magnitude of the contamination? Here it may be important to know the size of the spread of the contaminant in the environment and whether it degrades or bio-magnifies after entering the food chain. Any synergistic effects in the presence of other chemicals may also become crucial.
- What is the potential risk to human health and the environment? To be answered, this question needs detailed analysis of the release of potential contaminants in the different environmental matrices and consequently their environmental concentrations observed/modelled. Then the related possible exposure paths for the biota compartment (e.g. respiration, contact, ingestion) are analysed to assess the impact on human health and ecosystem.
- How much will the pollution cost? The total pollution cost includes two components: the damage cost and the remediation cost. The damage cost is the compensation to be paid for the death of, or injury to any person or damage to any property or environment. The remediation cost is the amount required to reinstate the environment to its pre-pollution state.
- What is the best strategy for clean-up and remediation? The strategy adopted for clean-up must be suitable for the contaminant and the polluted environmental matrix. The cost involved, disturbance caused to the soil, long-term effectiveness, time requirement, etc. are important considerations.
- How should the costs be allocated amongst the responsible parties? Environmental forensic investigations involve identifying the parties responsible for pollution and, determining the share of each party towards the total pollution cost.

Issues of risk and uncertainty are at the centre of large parts of environmental regulations. With the help of environmental regulation, we can ensure that risks are identified and assessed, and that measures to manage the risks are taken. Legal rules can also govern which measures are taken by requiring that the best possible technology be used. Risk assessments are also important as a starting point for determining safe actions and condition e.g. in obtaining a permit for environmentally hazardous activities. Risk assessments however also feed into the actual law-making process, as these types of assessments are important when it comes to deciding on what regulation to adopt, e.g. regulations on hazardous substances. From this perspective, the risk assessment that forms the basis for the environmental legislation will also contribute to direct the use of limited resources against the most significant risks (see e.g., Russel and Gruber, 1987).

Currently in environmental regulation it is important to assess the impact of a product/service/etc. not only considering their use but the whole life cycle. In addition, consideration should be given to the different environmental aspects (such as global warmings; biodiversity loss; ocean acidification; etc.) with the same assessment methodology. This is the case of a life cycle assessment.

The current column aims at investigating the applicability of RA and LCA in the environmental forensic field whilst highlighting the special characteristics of each method.

2. ANALYSIS OF THE TWO DECISION TOOLS

In the following paragraphs a brief description of the two tools is presented and the similarities and differences are compared. In Table 1, the detailed characteristics of RA and LCA are reported.

2.1 Risk Analysis (RA)

The mathematical definition of risk is mutable in different fields of applications (volcanology, seismic analysis, woodland burn, transport, ecological, nuclear, chemistry, industrial and sanitary engineering, etc.) and with proper care we need to apply the correct definition to each different field (Glickman, 1990; Asante-Duah, 1998; Salandin, 2001).

A general quantitative definition for the Probabilistic Risk Assessment defines the risk as as the product of a frequency times the magnitude of the events ' (Rasmussen, 1981; Asante-Duah, 1998; Glickman and Gouch, 1990; Paustenbach, 2002):

$$R = F \times M$$

where:

- R is the risk of the system (consequences/ unit time);
- F is the frequency that an adverse event can happen (event/ unit time);
- M is the magnitude of the consequences of the event (consequences/event);

Sometimes it is more useful to use the probability (P(H)) that an adverse event of a determined intensity can happen in a specific period of time (Varnes, 1984) rather than the frequency of events by year (F). In this case the previous definition becomes:

$$R = P(H) \times M$$

Therefore, the tool is rooted in two analytical approaches: probability theory and methods for identifying causal links between adverse health effects and different types of hazardous events/activities.

Environmental risk can be clearly distinguished from ecological and human health risk. According to EPA, ecological risk assessment (ERA) is the process “that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors” [EPA, 1996] and in general it can be considered a systematic process to organize and analyse data, information, assumptions and uncertainties for the purposes of evaluating the probability that some adverse effects to the analysed ecosystem will take place [Suter, 1993].

The term “adverse” is understood as a negative alteration to the structural and/or functional features of the ecological system examined. Conversely, the term “stressor” refers to an unwanted human action (of chemical, physical or biological type) leading to an unfavourable effect.

Health risk analysis aims at investigating the effects on humans. Risk analysis can distinguish between the effects of a dangerous event in a determined point, hypothesizing the potential presence of a human (individual risk) and the negative effects on the general population in the area of study (diffuse or collective risk).

In the last few years, human health risk analysis has developed further, often hand in hand with ecological risk analysis, as most pollutants, known to have an impact on the ecosystem, have also impacts on human health and vice versa. Nevertheless, it has been shown that a lot of contaminants (ammonium, chlorine, some pesticides, etc.) that have minimal effect on human health, can cause serious damage to aquatic organisms.

Finally, a distinction that should be highlighted is between "predictive risk assessment" and "retrospective risk assessment" (Asante-Duah, 1998; Erskine, 1997; Glickman and Gouch, 1990; Henley and Kumamoto, 1981; Paustenbach, 2002; Rasmussen, 1981; Suter 1993). In the first case, the analysis refers to the effects that could occur with the occurrence of adverse events. In the second case, the analysis is referred to environmental effects due to an event that has already occurred.

The procedure of "predictive risk assessment" involves structuring the risk assessment into two distinct phases. One phase assesses the probability of system failure, and a second phase predicts the effects on humans and/or the environment.

The procedure of "retrospective risk assessment" initially involves verifying through environmental monitoring the release of pollutants, for example from a landfill system, and assessing the level of contamination of adjacent environmental matrices.

There are some examples in the scientific literature of advanced environmental monitoring methods that also support forensic activities and, above all, allow to obtain quantitative results, useful for both methods (Persechino et al., 2013, Di Fiore et. Al, 2017).

The evaluation of damage to humans or the ecosystem resulting from the contamination is the next stage of analysis.

The full operating methodology subdivides the risk assessment into the following phases:

- **System Reliability:** it is the study of the probability of system failure (for example, a bottom liner break of a landfill causing leachate leakage; break of the air pollution control system causing the uncontrolled emissions of contaminants from the stack of a plant; etc.) by means of non-deterministic techniques. If the adverse event (failure of the system) has already happened, this phase is not explicitly required. This phase is present only in the "predictive risk assessment".
- **Hazard Identification:** it concerns the identification of the chemicals which are responsible for the potential contamination on the environment.
- **Hazard Assessment:** it is the evaluation of the hazard of the released contaminants divided in two parallel steps: the "exposure assessment" and the "dose-response assessment" (or "toxicity analysis").
  - The exposure assessment estimates the concentration of the contaminants in the environmental matrixes in correspondence to the exposition points to evaluate the level of exposure by organisms, including humans, for the given situation.
  - Dose-response assessment estimates the incremental effect of the dose of contaminants by means of ecotoxicological survey, epidemiological studies, etc.
- **Risk characterization:** it estimates the comprehensive risk, its eventual tolerability, the risk perception and the uncertainties.

There are several standards for risk assessment, but some of the most relevant ones include:

- The (U.S.) National Academy of Sciences (NAS), 1983. Risk Assessment in the Federal Government: Managing the Process.
- European Commission, 2003. Technical guidance document on risk assessment - part II, Technical Guidance Document on Risk Assessment.
- EPA, 2000. Science Policy Council Handbook. Risk characterization.
- ECHA, 2013. Guidance for human health risk assessment volume III, part B : guidance on regulation (EU) no 528/2012 concerning the making available on the market and use of biocidal products (BPR).
- EPA, 2011. Exposure Factors Handbook.
- EPA, 1998. Guidelines for Ecological Risk Assessment.

2.2 Life Cycle Assessment (LCA)

The Society of Environmental Toxicology and Chemistry (SETAC) was one of the first international organizations which developed the life cycle assessment (LCA). In 1991, it defined the life-cycle assessment as "*an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, use/re-use/maintenance, recycling, and final disposa*l."

Later the organization (SETAC, 1993) further developed the above statement, defining LCA as "*one of the tools used to examine the environmental cradle-to-grave consequences of making and using products or providing services.*"

Currently, the ISO 14040 (2006) defines the LCA as "*the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*".

The operating methodology subdivides the LCA into the following iterative phases:

- **Goal and scope definition:** it is the definition of the objective of the study, its intended application,target audience and the specific system to be investigated. Further the functions, the functional unit (unit used as the reference in the study that represents the function of the system) and the system boundaries (processes of the system to be included in the study), are set.
- **Inventory:** it involves collection of the input/output data and related information from each process in line with the goals of the defined study. The life cycle invento-

ry modelling framework can be identified as: 1. "attributional", depicting the system as it can be observed/measured, in which the single processes within the technosphere are linked by materials, energy and services flows; 2. "consequential" which aims to identify the consequences of a decision in the foreground system on other processes and systems of the economy, and builds the to-be-analysed system around these consequences.

- **Impact assessment:** in which input and output of the processes included in the boundaries are characterized to represent their potential consequences on the environment. Several characterization methods can be implemented to represent a comprehensive view of the potential environmental impacts of the system beingin-vestigated. Results can be represented at a mid-point level, showing the potential risk of having consequences on specific impact assessment categories (e.g. climate change, freshwater eutrophication etc.) or at end-point level, showing the potential consequences for human health, ecosystem quality and depletion of resources.
- **Interpretation:** in which the results of the analysis are evaluated in terms of soundness and robustness, and overall conclusions, recommendations and decision-making are drawn in accordance with the goal and scope definitions.

The most relevant technical standards are:

- ISO 14040. Environmental Management – Life Cycle Assessment – Principles and Framework (ISO, 2006).
- ISO 14044. Environmental Management — Life cycle assessment — Requirements and guidelines (ISO, 2006).
- ISO/TS 14072. Environmental management — Life cycle assessment — Requirements and guidelines for organizational life cycle assessment

Important technical documents are also represented by:

- the ILCD Handbook – General Guidance for Life Cycle Assessment – Detailed guidance – JRC – EUR 24708 EN – 2010
- The ILCD Handbook – Recommendations for Life Cycle Impact Assessment in the European Context – JRC – EUR 24571 EN – 2011.

2.3 Similarities and differences

There are some key similarities and differences between the two tools, an overview of these is given in Table 1. In terms of methodology, the two approaches are both primarily technical-scientific assessment tools, concerned with quantitative modelling the potential or actual environmental impacts on the ecosystem. The results of both approaches may be presented as a single score impact index related generally to a single consequence (e.g.

TABLE 1: Comparison between Risk Analysis (RA) and Life Cycle Assesment (LCA).

Characteristics	Risk Analysis (RA)	Life Cycle Assesment (LCA)
Definition	Although RA has a long history of use, there is no commonly accepted definition of risk and its mathematical formulation is mutable according to the different fields of applications. A general, but well-used definition, describes the risk as the product of a frequency (or probability) and the magnitude of the adverse event.	Unlike RA, the definition of LCA has been agreed upon, at the international level, since the early 1990's. . LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040:2006)
Aim of the methodology	RA quantifies the likelihood and severity of harm associated with a product, process, activity (e.g. smoking), agent (such as pollutants in different media), or an event (leakage of leachate from the bottom of a landfill). In environmental risk assessments, both the potential exposure and the hazard associated with a chemical or chemicals, in specific release scenarios, are estimated. RA focuses principally on receptors.	LCA estimates potential impacts, in diverse categories, by aggregating material and energy inputs and outputs from all the processes that take place from the start to the finish of a product/service, and reports these impacts relative to the function or service provided. LCA focuses principally on emitters.
Object analyzed	In RA, the object may additionally include "natural" products, processes, activities. Alternatively chemicals (synthetic and naturally occurring pollutants) and events (such as floods and earthquakes) may be included.	The object analyzed in LCA can be the life cycle of a product/service, or the activities of an organization also described as a "product system". A product system is defined as a "collection of materially and dynamically connected unit processes which performs one or more defined functions" (ISO, 2006).
Perspective of the analysis	Prospective analysis looks forward in time Retrospective analysis looks back in time	Prospective analysis looking forward in time can be implemented into LCA methodology adopting additional specific methods (system dynamics, etc.)
Scales of investigation	Typically RA focus on local scales with site-specific data generally being used in the models.	LCA requires generalized models and assumptions that lack the specificity typical of RA.
System boundaries: Spatial modelling	Spatial modelling of the related impacts (such as human health effects due to emissions) may or may not be site specific in RA.	Regionalization of impacts is related to specific impact assessment categories such as water scarcity. Generally, most of the category indicator results are not site specific.
System boundaries: time modelling	RA tends to focus on an endpoint (or endpoints) defined in time.	LCA results are integrated over time and hence give no information concerning the timing of impacts.
Outcomes	The outcome can be a numerical estimation of the likelihood of a specific harm or a comparison with criteria to define whether the risk is acceptable.	The outcomes include resource use (not present in RA), human health, and ecosystem quality .
Uncertainties	Uncertainties is considered in two aspects: the probability that an adverse event can happen and the ones related to the inputs values, for example, in transport and exposure modelling	Uncertainties is used to understand the variation of the parameters. Uncertainty is influenced by several factors including value choices (e.g. weighting factors). LCA Interpretation includes uncertainty analysis to investigate the robustness of results and therefore support the conclusion to be drawn.

global warming; risk estimates related to the exposure of a non-carcinogenic compound; etc.) or by a series of impact indicators grouped per each investigated compartment (e.g. environment, resources depletion and human health). Besides, additional models (such as statistical analyses of uncertainties in data) may be used to interpret and evaluate the results.Both tools include the same general stages of process (problem identification, problem formulation, modelling, implementation, interpretation, feedback), but the operative steps are different (see above paragraphs).

LCA differs from RA in the information it provides to support decision making. LCA is mainly, but not exclusively, focussed on identifying possible improvements in a life cycle perspective rather than to compare the results against absolute standards and/or reference values. In RA, the absolute magnitude of the event under study is often a fundamental component in the analysis, and the "acceptability" of the risk, rather than identifying potential improvements , is of more interest.

There is an intrinsic difference in the scope of the two tools: LCA estimates several potential impacts of a system (products, services) from its whole life, using assumptions and information that most of the time are not site specific and considered to be marginal if compared to the pristine environmental conditions; while RA focuses on the concept of risk of a system (a plant, a contamination event, an activity, etc.) in a specific time and place.

Consequently, the outputs (aggregated or not) of RA are more site-specific and focuses on receptors, while those from LCA are generally integrated over time and space and focuses principally on emitters.

3. CONCLUSIONS

Life cycle assessment is motivated by gaining an understanding of the systemic environmental consequences of a product, process or service that fulfils a valuable economic or social function; LCA allows for a broader and more integrated overall view. Therefore, it is readily applied in identifying viable alternatives (e.g. a process, material, technology), evaluation of mitigation activities, its reporting and environmental management.

On the contrary, risk assessment is motivated by risk reduction and it allows for greater clarity on the risks associated with a given condition, defining the associated hazards and quantifying the consequences. RA is often applied in regulatory compliance and therefore it has a wider application in environmental forensics.

Table 2 reports a collection of common questions in the framework of environmental forensics and indicates whether the two tools can be used to provide an answer.

While recommendations to integrate the two approaches have remained a consistent challenge for the scientific community for at least 20 years; this is primarily due to the differences between the two tools. A more pragmatic approach is to apply the two methods in parallel, integrating only after obtaining separate results. This can be done by a multi-criteria decision analysis (MCDA), which can be defined as family of methods, designed to reveal the complicated trade-offs or compromises inherent in complicated problems.

In summary, LCA and RA are two approaches with different peculiarities, each one more oriented in giving responses in specific contexts; for this reason, the first cannot substitute the second and vice versa. An integrat-

TABLE 2: Application of RA and LCA in environmental forensics.

Common questions in environmental forensics	RA	LCA
What was the source of the contamination?	YES In the retrospective risk analysis we are able to identity the sources in terms of chemical typologies	NO LCA can help to better understand which of the processes involved is potentially related to the possible emission of the contaminant
When did the release occur?	YES In the retrospective risk analysis a transport model can be used to reconstruct the history of chemical transport	NO
How did the release occur?	YES In the retrospective risk analysis, by means of a transport model, it is possible to reconstruct the modality of transport in the different media and understand exposure during this transportation.	NO
Who contributed to the problem?	YES (partially) Knowing the history and modality of the chemical transport we can identify the potential polluter(s)	NO LCA can help to identify in a given system the processes probably related to the problem
What is the extent and magnitude of the contamination?	YES In the prospective risk analysis, we can assess the magnitude of the potential damage when the adverse event occurs	NO
What is the potential risk to human health and the environment?	YES	YES But unlike RA, LCA is not site specific
How much will the pollution cost?	Partially With the risk assessment we can estimate the reduction of risk by applying some strategies and therefore the relative costs	NO
What is the best strategy for cleanup and remediation?	YES With the risk assessment we can estimate the reduction of risk by applying different strategies for clean-up and remediation	YES With LCA it is possible to compare the different systems used for the remediation
How should the costs be allocated amongst the responsible parties?	YES If investigations reveal the presence of polluting chemicals at a site, an exposure assessment (a stage in RA), will help in assessing the amount of pollutants to which the parties claiming damage have been exposed to, through the various routes of ingestion, inhalation, and dermal contact. Once the exposure is quantified, established dose-response models can be used to evaluate if the health impacts alleged are the result of exposure to the pollutants or not. In other words, it is possible to make a comparison between calculated risks through the RA procedure and alleged risks in order to evaluate the claims from both the suspected polluters and of the affected parties. Thus, RA provides a scientific tool for the appraisal of damage claims, leading to correct decisions.	NO

ed approach can lead to deeper information about a given phenomenon and on how some impacts can be or have materialized; this is an important part of environmental forensics and as such, it is suggested that further exploration into the use of these tools be completed.

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