Editorial

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Transition to circular economy requires reliable statistical quantification and control of uncertainty and variability in waste

A circular economy involves the closing of material loops or cascading used resources, transforming waste into new (secondary) resources, or even preventing waste from occurring in the first place. Here, we analyse the interface between the concepts of circular economy, 'uncertainty' and solid waste, looking at multiple approaches. We emphasise that effective and scaled up transition to a circular economy is fundamentally unfeasible without understanding and quantifying both uncertainty and variability. This quantification, in turn, depends on the existence and availability of relevant theoretical and practical tools, such as the standard description of variability for solid flows, the so-called 'Theory of Sampling' (TOS), initially developed for practical needs of the mining industry; and on the skill set and funds required to operationalise those tools. The vital reason behind this prerequisite is that waste streams are almost always considerably heterogeneous and will therefore always exhibit high (even extreme) levels of variability.

The tough feature of 'waste': Heterogeneity

The concept of (solid) 'waste' is inextricably related with physical variability, heterogeneity. Such variability refers to both (i) an inherent, internal variability within the mass of the solid waste, most evident in layman's terms as mixed products randomly thrown together in a waste bin (e.g. a newspaper (paper), a wine bottle (glass) and a water bottle (plastic)); and (ii) a barrier introduced by 'matter out of place' (e.g. a pile of food leftovers thrown on dining table): An abrupt interface is introduced between the ambient environment and the solid waste, in the sense that these components are fundamentally different, the presence of waste preventing the ambient environment to function in its normality. Among everything else, waste challenges the absorptive capacity of the environment (e.g. a pile of green waste left on a pavement would take too much time to disintegrate and disappear to allow for the pavement to serve in its fundamental role: Walking corridor for pedestrians).

Waste variability can in one view be perceived as a 'distance from normality' (i.e. an irregularity) that results before, during or after a product use. For example, 'irregular' shapes of vegetables become 'waste' for the purposes of tightly defined supermarket standardised produce; a plastic cup contaminated with coffee residues after its use; a partially torn book, while still readable can become waste; or a scratched music CD, that cannot be correctly played any more. Incidentally, these are more complex aspects of waste variability than the standard compositional and spatial heterogeneity concepts usually encountered in the TOS. We here, therefore, initiate the development of an augmentation of standard TOS approaches to heterogeneity.

Waste-derived resources and statistical quality management

Solid waste occurrence typically starts with bringing together previously unrelated materials, by depositing them together in a collection bin. But, the act of juxtaposing waste components is not synonymous with mixing them, thus often resulting in a 'lot' (mother population of discarded objects) of high variability. Markets value relatively pure waste-derived materials, that differ as little as possible from the virgin raw materials. As a result, significant downstream processing efforts are very nearly always needed, specifically with the aim to reduce variability – primarily by sorting, disassembling and shredding operations, without which there can be no material value recovery.

In this sense, a materials recovery facility (MRF), where dry recyclables are sorted, is the paramount archetypical operation for circularity. Proponents of circularity invest capital and operational resources (buildings, equipment, energy, water, human capital, etc.) to *reverse* the increased entropy damage incurred by the unfortunate, unavoidable waste bin 'mixing moment'. The same applies to waste pickers (informal recyclers, who perform this function at another level and with mainly manual means throughout low-income countries worldwide). Starting from a highly variable plant input, the fundamental aim of these operations is to generate a number of more useful and valuable output flows, each with decreased heterogeneity (i.e. more of similar things put together). However, there will always be *some* contamination in each of the outputs, or in TOS' parlance, residual heterogeneity.

In this context, the salient question arises: Is it feasible to achieve any desirable level of purity (and in a wider sense, any quality) within the available budget and considering effectiveness of processing? To describe the quality of the outputs for such a sorting process, quality monitoring tools are imperative, but what kind of tools (statistical, data analytical, process analytical) are optimal? Such tools are commonplace in the materials and products manufacturing industries, but they are still in their infancy when it comes to mixed (municipal) solid waste and its processing. It has been long understood that materials separation in the waste sector has been inefficient (e.g. higher to extreme heterogeneity, considerable cost of analytical testing, in comparison with the possible profit margins). The perceived severe difficulty of representative sampling of mixed solid flows has played a dominant role. It should be clear, however, that attainment of a circular economy means that effective waste sorting operations are no longer seen as burdensome costs, but instead as the cornerstone of transforming *waste processing* into *manufacturing*, capable of delivering quality-controlled and assured output flows

– in exactly the same manner that primary resources, raw materials, are produced and traded with their respective quality assurances.

However, which is the necessary toolkit for this transformation, and where can it be applied to make it possible to structurally transform solid 'waste' processing? Below we deal with only some of the technical aspects, fully acknowledging that there are other major drivers that also must be addressed, not least organisation/governance aspects (e.g. policies, regulations, and citizen/ consumer involvement).

Multiple approaches and tools

In the process of transforming solid waste into new resources, one can apply a variety of existing tools that capture and describe variability, giving us the opportunity to effectively minimise it, where feasible. To list the immediate major options: General descriptive and multivariate data analysis and statistics, including nonparametric descriptions robust to extreme values, statistical design of experiments (DoE) and in a wider context, chemometrics, TOS, error propagation, data reconciliation, 'measurement uncertainty' (MU), Monte Carlo simulation and statistical quality control. While it is beyond the present scope to discuss all of these, we selectively comment upon a few that appear to represent the most promising possibilities.

Our fundamental proposition here, is that there cannot be a sufficient understanding of solid waste properties and the potential to turn waste into secondary resources without a reliable and effective description of its variability. This is an absolute necessity. Point estimates of average values are generally insufficient for this purpose. It is critical to reliably quantify the inherent variability around estimated average values. In many cases also, the parameters chosen to represent the waste heterogeneity are not normally distributed (i.e. would not follow a Gaussian distribution). One traditional way to try to overcome this is to employ so-called 'robust' data analysis (statistics), i.e. variability descriptions that are not sensitive to extreme values, to use non-parametric statistics (e.g. the use of quartiles), or to take into account the shape of the distributions. However, in most cases, there is only extremely limited information (or often none at all) on the type of distribution that one might feel compelled to apply, perhaps from a theoretical and/or practical point of view.

In addition, there is a fatal misunderstanding to some of the traditional approaches, a blow that comes from a comprehensive understanding of heterogeneity. Following the TOS in necessary detail, a heterogeneous lot *cannot* be reduced to a traditional statistical distribution (Gaussian, symmetric or skewed) of just *analytical determination results*. Such a view is, at best, overly simplistic, and, at worst, useless; that is when heterogeneity really shows it teeth – precisely the case with solid waste. This is due to two major contributors of uncertainty involved: (i) the analytical measurement uncertainty, MU_{an}; and (ii) the uncertainty associated with sampling (including sub-sampling and sample preparation), MU_{sampl}. Two facts from real life fundamentally challenge traditional understandings and practices: First, MU_{sampl} is *always* much larger than MU_{an}, typically 10–25–50 times larger and, as a result, completely dominates any and all 'measurement error budget'. In fact, this particular challenge actually scales up in the case of solid waste material, because of their high inherent heterogeneity. Second, MU as it is practiced today, almost exclusively disregards MU_{sampl} (or it only includes one of the five 'sampling error' effects considered in TOS, most unfortunately just the smallest one). There has been a serious ongoing debate between MU and TOS for decades – only recently reconciled by a comprehensive analysis (Esbensen and Wagner, 2014). We return to this much-needed reconciliation at several occasions as we advocate the development of an improved approach to quantifying waste heterogeneity and proper waste sampling – before any analytical determination stage.

Educational needs for uncertainty quantification: TOS

In any case, when we try to quantify via a measurement process (e.g. measure the concentration of a potentially toxic element, such as cadmium, via an analytical determination in the laboratory), we cannot just report a single value, but also the error associated with this measurement, a factor of equal importance. The scientific fields of metrology and statistics address such aspects via the concepts of *accuracy* and *precision*. The field of measurement uncertainty has traditionally been used to quantify the 'measurement error'. Any subsequent characterisations or calculations involving properties identified via analysis should, in principle, involve the use of pertinent error propagation approaches.

There are still considerable training needs for researchers and investigators into correct and complete assessment of uncertainty. It is unsettling that the vast majority of the research studies report only MU_{an}, almost completely neglecting the dominating MU_{sampl}. A recent publication assessed the current approaches to MU with respect to the complete ensemble of sources affecting the measurement process (Esbensen and Wagner, 2014), in particular the extent to which sampling errors, as set out in TOS, are appropriately considered in the international standards, guides and norm-giving documents. All pre-analysis sampling steps are important, collectively dominating the MU_{total} estimate. TOS constitutes the only complete theoretical and practical framework for competently dealing with the entire pathway from field (lot) to analysis (test portion) (Esbensen and Wagner, 2014).

In addition, when it comes to applying TOS in the realm of solid waste, many more empirical examples are needed in order to get a fundamental database on how to correctly quantify (calibrate) the various parameters involved. In this regard, we are still on a steep learning curve. The emergence of sensor-based, in-line, real-time characterisation equipment (e.g. near infrared-based (NIR)) does not negate the need for TOS – on the contrary, TOS is needed for the correct interpretation of the results, for example in combination with techniques such as variograms.

'Circularity' and information uncertainty

We aim to introduce the complete, complex framework outlined above in the service of a circular economy. While far from the only factor, proper, i.e. representative, sampling nevertheless emerges as the crucial, element in this endeavour, without which all hopes for efficient and reliable materials characterisation is lost, significantly reducing the possibilities for competitive economics in resource recovery from the waste sector. Answers to several major challenges are needed, for example most waste processing plants do not have an effective way to control, or even assess to begin with, the level of variability of materials accepted as input. Solutions to this direction require competent understanding of the salient issues regarding sampling and sub-sampling – which for solid mixture flows (as indeed for any type of heterogeneous lot material) – is accomplished only by the TOS (DS 3077, 2013).

Innovation, analytical laboratory and DoE

From solid waste we can recover secondary engineered technical materials, chemical compounds that can be used as feedstock to materials production, soil improvers with fertilising capacity (nutrients / humic substances) and fuels used to produce energy and heating/cooling. Major innovation for a genuine circular economy can only be based on a compound and materials level, and can be extended only to a limited degree via reuse, repair and remanufacturing.

When working with solid waste samples in a laboratory, there are increased challenges in accurately quantifying analytes, both for innovation, but also for environmental compliance. Usually, there are increased phenomena of interferences. The heterogeneity of the components contained in the final test samples derived from solid wastes, often results in unacceptably high relative standard deviation (%RSD), requiring multiple authentic replications to limit such variability. Despite these well-known limitations, and relevant longstanding efforts since the 1970s, there are still no universally acceptable and sometimes suitable reference materials and/or standard methods or just standard operating procedures for solid waste characterisation, which prevents accurate determination of analytes and increases the spread of the results.

However, there is a revolution in the offing – much of this apparent variability (the dominating proponents) is in fact *not* an analytical issue: Imperfect, improper (non-representative) sampling is the root cause of the overwhelming part hereof. Learning how to deal with unnecessary and controlling sampling errors (reducing or eliminating specific sampling errors is the central tenet of the TOS) will turn these challenges into victories. TOS applies just as much in the laboratory as in the field (DS 3077, 2013).

At this level, it is also important to employ statistically designed experiments (Design of Experiments: DoE) where relevant, using tools such as screening tests, fractional designs to accommodate for complex multi-variable systems, dual (controlling for both averages and spread) response surface methodologies to develop empirical models, to identify global optima and account for interactions. But, no matter how powerful or necessary such statistical analysis tools are (Velis et al., 2014), to date they have just seen very limited application to the waste reprocessing sector research and development. A likely reason and key limitation could again be identified as a much-too-high and unnecessary component of sampling-and-analysis errors, making data obtained very 'noisy' (relatively high unaccountable error). Contrary to traditional statistical thinking, just 'more samples, more data', will *not* solve this problem – only better data, i.e. from representative samples and thorough conceptual quantification of sources of variability, for example during sub-sampling before analytical determination. This is perhaps the most important lesson from the TOS (DS 3077, 2013).

Evidence-based policies and uncertainty quantification

Understandably, policy and decision makers often have a clear preference for simple coherent stories, numbers and tools. It is, indeed, the role of scientists and engineers to cut though the complexity of our world and come up with comprehendible theories and applicable solutions. However, there is no practicable way to remove altogether the variability and uncertainty from our world. Politicians demanding one, certain, number before political action can be contemplated must surely soon be a thing of the past (e.g. '2 degrees Centigrade'). More effective government actions could undoubtedly emerge if politicians learn, apply and deploy policies considering not just single 'average' numbers, but also the uncertainty around them – signifying a level of confidence.

Indeed, a major part of environmental protection, for instance regarding from emissions from waste-derived materials, considers compliance statistics and is in the right direction: As but one example, the European Committee for Standardisation (CEN) classification standard for environmental performance of solid recovered fuels (SRF) with regard to mercury (Hg) content, considers both the average (median) as well as a measure of the higher values (80% percentile), because of evidently non-normally distributed mercury concentrations. And many other systems analysis tools, such as life cycle assessment, are just starting to include a more complete uncertainty quantification.

To this direction, Monte Carlo simulation can be a powerful tool toward understanding the variability in systems or just even policy formulas, such as the EU Waste Framework Directive R1 clause, for energy from waste plants (EfW), helping us recognise that the choice of every mathematical formula has inherent implications on its potential outcomes, which should be studied *before* any adoption. However, all simulations have an in-built weakness, such as the unknown reality of the underlying distribution from which the Monte Carlo approach draws its innumerable 'realisations'. The degree to which the standard statistical distributions used are valid representations of reality, is a non-trivial issue.

When it comes to protecting human health and the environment within a circular economy, the risks and impacts associated for example with circulating materials containing potentially toxic elements/compounds or dangerous persistent organic pollutants (POPs), need to be competently assessed. As does risk assessments, for example regarding genetically modified organisms (GMOs). An illuminating example of putting TOS in play in this latter context can be found in Minkkinen et al. (2012). Epidemiological studies are also necessary, where the co-founding factors have to be carefully considered. The complex statistics involved can be off-putting to many researchers. To date, only a very few relevant robust studies have been seen exploring potential health implications of waste-derived products or emissions from solid waste re-processing to close the materials loop. To us, such knowledge, informed by vigorous statistics, is of utter importance if a circular economy is not to become just another vehicle for pollution dispersion; yet it does not necessarily receive the attention required by the global academic and policy-making communities.

No doubt, there is a lot to be done so that the waste and resources management sector can benefit from a reliable quantification of uncertainty and minimisation of variability, to best serve its role within a circular economy. Do keep an eye on *Waste Management & Research*, as we will be regularly including articles on this crucial topic.

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