# Preserving Metrological Traceability in Industrial Reporting Systems: A Framework for Sequential Cumulative Dosing

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## Abstract

Digital weighing systems in computerized manufacturing environments typically report measurement results as single numeric values, creating an appearance of precision that may not be supported by the underlying measurement system. This becomes particularly significant in sequential cumulative dosing systems, where multiple weighing events are combined to form a single batch quantity.

In sequential cumulative dosing, individual measurements are not independent. Each dosing event contributes to an accumulated platform weight that serves as the reference condition for subsequent ingredient additions. Consequently, uncertainty associated with earlier dosing events propagates throughout the batching sequence. When uncertainty is not evaluated and recorded at the point of measurement, it cannot be propagated through the process or reconstructed from historical production records.

In the dosing system investigated, the SCADA implementation contains no embedded measurement uncertainty model. As a result, dosing records and manufacturing reports present cumulative dosing data as deterministic quantities without representation of the underlying measurement uncertainty, creating a disconnect between reported values and the metrological capability of the measurement system.

This paper identifies uncertainty propagation as a metrological challenge unique to sequential cumulative dosing systems and proposes a GUM-consistent conceptual framework in which uncertainty is evaluated at individual dosing events, propagated through the cumulative dosing process, integrated into SCADA records, and incorporated into manufacturing reports. The framework provides a structured basis for improving the metrological completeness and interpretability of manufacturing data.

Keywords: Sequential Cumulative Dosing, Measurement Uncertainty, SCADA, Manufacturing Reporting, Metrological Traceability, GUM, Weighing Systems, Automatic Dosing, Production Data Interpretation, Feed Manufacturing

## Introduction

Animal feed manufacturing relies on precise ingredient dosing to ensure product consistency and nutritional compliance. In computerized feed mill environments, dosing processes are managed through SCADA systems that control and record the weighing of individual ingredients into batches. These dosing processes, in which multiple ingredients are individually weighed and accumulated in sequence into a single batch receiver — herein referred to as sequential cumulative dosing systems — are a common practice in automated commodity weighing [1][2]. The accuracy of these processes has direct implications for product quality, regulatory compliance, and operational efficiency.

This paper originates from observations made within a large-scale animal feed manufacturing company operating more than 30 production facilities across Indonesia. Two operational parameters governing the dosing weigher system have been applied consistently across these facilities for approximately three decades. The first is a maximum permissible error (MPE) of 0.2% applied as the calibration and accuracy test standard for all dosing weighers [2]. The second is a minimum dosing limit, expressed as a percentage of weigher capacity — set at 2% for macro ingredients and 4% for micro ingredients — below which ingredient assignment to a given weigher is not permitted. Despite their long-standing application, no formal metrological documentation exists to explain the basis of these parameters or the relationship between them.

Through literature research and conceptual analysis, this study identifies that both parameters are connected through the concept of measurement uncertainty [3]. The maximum permissible error of a weigher, together with its capacity, can be used to derive an uncertainty factor for each individual weighing event [2]. This uncertainty factor, when compared against formula tolerance, establishes a metrological basis for the minimum dosing limits — an ingredient amount below which the dosing result cannot be guaranteed to fall within the specified formula tolerance.

This investigation further reveals two distinct problems in how dosing results are currently reported. In detail batch reports, each dosed weight is treated as an exact quantity. No uncertainty is recorded or considered at the level of individual dosing events, and compliance with formula tolerance is assessed deterministically. This becomes particularly problematic given the sequential cumulative nature of the dosing process, where each ingredient is accumulated with previously dosed ingredients, and uncertainty from each event propagates through the cumulative total [3]. In aggregated production reports, while it is implicitly acknowledged that measurement results may not be exact, the error tolerance applied is a blanket figure with no documented metrological foundation. Furthermore, this blanket tolerance does not account for the nature of sequential cumulative dosing, in which uncertainty behavior differs fundamentally from that of a single isolated measurement.

Both problems share a common root cause: the SCADA implementation in the dosing system under study lacks an embedded measurement uncertainty model capable of evaluating uncertainty at the level of individual dosing events. Without such a model, uncertainty cannot be recorded, propagated, or incorporated into reporting systems in a metrologically sound manner.

This paper proposes a GUM-consistent measurement framework [3], [4] for sequential cumulative dosing systems, in which measurement uncertainty is evaluated at each individual weighing event based on instrument characteristics and operating conditions, and propagated traceably through the cumulative dosing process. The framework provides a structured basis for integrating uncertainty information into both detailed batch reports and aggregated production reports, thereby improving metrological consistency in manufacturing data interpretation.

The remainder of this paper is organized as follows. Section II reviews relevant literature on measurement uncertainty and dosing systems. Section III identifies the research gap addressed by this study. Section IV presents the proposed methodology and framework. Section V presents the results and conclusions.

## Literature Review

### A. Measurement Uncertainty in Weighing Systems

Measurement uncertainty is a fundamental concept in metrology, defined in the Guide to the Expression of Uncertainty in Measurement (GUM) as a parameter associated with the result of a measurement that characterizes the dispersion of values that could reasonably be attributed to the measurand [3]. The GUM establishes that a measurement result is only complete when accompanied by a statement of its uncertainty — a single numeric value without uncertainty information provides an incomplete representation of the measurement [3].

In the context of weighing instruments, measurement uncertainty arises from multiple sources, including instrument resolution, repeatability, environmental influences, and calibration uncertainty. The relationship between these sources and the overall uncertainty of a weighing result is governed by the law of propagation of uncertainty, which defines how individual uncertainty components combine into a combined standard uncertainty [3].

Legal metrology frameworks establish maximum permissible errors (MPE) as the basis for instrument verification and calibration acceptance criteria. OIML R 61-1 defines MPE as the extreme value of measurement error permitted by specifications or regulations for a given measuring instrument or measuring system, expressed in automatic gravimetric filling instruments as the maximum permissible deviation of each fill from the average value of all fills in a test sequence [2]. However, as noted by Mettler Toledo, the MPE defined in legal metrology frameworks represents a threshold for instrument approval, not a direct measure of measurement uncertainty in process applications [6].

The relative MPE of a weighing instrument follows a hyperbolic relationship with applied load, becoming disproportionately large when the dosed quantity represents a small fraction of the weigher's capacity [6]. This characteristic has direct implications for ingredient dosing applications, where assigning an ingredient amount below a certain percentage of weigher capacity results in a relative measurement uncertainty that may exceed the required formula tolerance.

The concept of minimum weight addresses this directly. It is defined as the smallest net sample mass that can be weighed on an instrument while still complying with a specified relative process tolerance requirement — the point at which the relative measurement uncertainty of the instrument equals the required process tolerance [6]. This concept establishes a metrological basis for minimum load requirements in weighing applications, connecting instrument uncertainty characteristics to process quality requirements.

### B. Sequential Batch Weighing in Manufacturing

Automated batch weighing systems are widely used in manufacturing industries, including animal feed production, pharmaceutical manufacturing, and food processing. In sequential batch weighing — referred to in industry as gain-in-weight batching — multiple ingredients are dosed one at a time into a single weigh hopper, with the controller monitoring the cumulative weight of each successive ingredient addition [1].

NIST Handbook 44 Section 2.22 describes automatic bulk weighing systems as systems adapted to the automatic weighing of a commodity in successive drafts of predetermined amounts, automatically recording and accumulating the net weight of each draft [1]. While this classification explicitly excludes batching systems, it establishes the regulatory recognition of successive accumulative weighing as a distinct metrological category requiring specific technical requirements.

In manufacturing metrology, the accuracy of measurement data has direct implications for process control and conformity assessment. Imkamp et al. note that measurement uncertainty plays a major role in conformity assessment — the judgment as to whether a measurement result does not exceed specification limits — and that uncertainty must be considerably lower than the tolerance for a meaningful conformity statement to be made [5]. This principle is particularly significant in batch manufacturing contexts where ingredient quantities must fall within specified formula tolerances.

### C. Measurement Uncertainty in Manufacturing Reporting

The integration of measurement uncertainty into manufacturing reporting systems remains an underdeveloped area in production metrology. Imkamp et al. observe that GUM application has so far prevailed only in the field of calibration standards and reference measuring instruments, with simplified procedures frequently used in production environments that may lead to different results in practical application [5].

A complete measurement result requires three components — the best estimate of the measured value, the unit, and the associated measurement uncertainty [5]. In current industrial practice, digital weighing systems typically report measurement results as single numeric values, transmitting only the weight value through their output interfaces without any associated uncertainty information. This design characteristic means that downstream systems — including SCADA implementations — receive no uncertainty data to record, process, or incorporate into reports.

Mettler Toledo explicitly states that no calibration is complete without the determination of estimated measurement uncertainty, citing the International Bureau of Weights and Measures [7]. Furthermore, the determination of measurement uncertainty enables the identification of the minimum weight — a critical parameter for ensuring that weighing results fall within process tolerance requirements [6]. The absence of uncertainty information in production reporting therefore represents not merely an omission of supplementary data, but a fundamental gap in the metrological completeness of manufacturing records.

The development of measurement models consistent with GUM principles provides a structured basis for evaluating and propagating uncertainty through complex measurement processes [4]. JCGM GUM-6:2020 specifically addresses the development and use of measurement models, providing the methodological foundation for extending uncertainty evaluation beyond single measurement events to multi-stage measurement processes [4].

## Research Gap

Measurement uncertainty is a well-established concept in metrology, and internationally accepted methods for its evaluation and propagation are provided by GUM and GUM-6 [3], [4]. Previous studies have also recognized the increasing digital integration of measurement systems within manufacturing environments and the importance of uncertainty information for reliable interpretation of measurement results [5]. Imkamp et al. observed that the practical application of GUM has so far prevailed primarily in calibration standards and reference measuring instruments, while simplified procedures are frequently employed in production environments [5]. Furthermore, they emphasized that a complete measurement result requires three components: the best estimate of the measured value, the associated unit, and the associated measurement uncertainty [5].

Despite these developments, limited attention has been given to the implementation of measurement uncertainty within sequential cumulative dosing systems operating under SCADA-based manufacturing architectures. Existing literature provides methods for evaluating uncertainty at the instrument level [3], [4], discusses the role of uncertainty in manufacturing metrology [5], and establishes the relationship between weighing uncertainty and minimum weight concepts [6]. However, to the best of the author's knowledge, no literature was identified that specifically addresses the evaluation, propagation, recording, and reporting of measurement uncertainty within SCADA-based sequential cumulative dosing systems.

In the industrial system investigated in this study, measurement uncertainty is not embedded within the SCADA implementation. Individual dosing records, batch histories, and aggregated production reports contain only reported weight values without any associated uncertainty information. Consequently, uncertainty cannot be propagated through the cumulative dosing process nor reconstructed from historical production records. This creates a disconnect between the reported values and the metrological capability of the underlying measurement system.

This study addresses that gap by developing a GUM-consistent framework for sequential cumulative dosing systems, integrating uncertainty evaluation at individual dosing events, uncertainty propagation through cumulative batching operations, incorporation of uncertainty information into SCADA data records, and presentation of uncertainty information within manufacturing reports. The proposed framework aims to improve the metrological completeness and interpretability of production data while maintaining compatibility with existing industrial dosing infrastructures.

## Methodology

### A. Field Observation and Practitioner Inquiry:

This study is grounded in the author's 25 years of professional experience in industrial automation within a large-scale animal feed manufacturing environment. Direct observation of dosing system operation, SCADA architecture, and manufacturing reporting practices formed the primary basis for problem identification.

To verify the operational status of the two parameters under investigation, structured informal inquiries were conducted with colleagues across multiple operational roles, including production, quality control, PPIC, automation, and plant management personnel across several facilities. These inquiries were conducted through direct communication in May 2026.

The first parameter — a maximum permissible error of 0.2% applied as the calibration and accuracy test standard — was consistently confirmed across all facilities contacted. This parameter is universally accepted and not subject to operational dispute. However, no respondent was able to identify a formal documented source for its adoption, and its metrological basis within the dosing system context has not been formally established.

The second parameter — minimum dosing limits of 2% of weigher capacity for macro ingredients and 4% for micro ingredients — presents a more complex operational picture. While applied consistently as a national internal standard across facilities, this parameter is actively and recurrently challenged by production personnel, for whom the constraint limits flexibility in ingredient-to-weigher assignment. Quality control personnel consistently defend the parameter on the basis that values below the limit compromise measurement reliability. However, neither side has been able to articulate a formal metrological argument either supporting or opposing the limit. The parameter has remained in this contested state for more than two decades without formal resolution.

This persistent unresolved contestation — where a parameter is simultaneously enforced and challenged without documented metrological foundation — provides direct operational motivation for this study. Informal inquiries confirmed that no respondent across production, quality control, PPIC, automation, or plant management roles was able to identify a documented origin for either parameter. One respondent described the minimum dosing limit as "rule of thumb," while another attributed the 0.2% accuracy standard informally to quality control practice without reference to any formal document or standard.

Additionally, structural analysis of the SCADA dosing database was conducted to examine whether uncertainty information is captured at the system level. The dosing transaction record structure was examined for the presence of uncertainty-related fields alongside standard process fields including weigher identifier, ingredient identity, requested weight, delivered weight, deviation, and tolerance status. This analysis confirmed the absence of any uncertainty parameter within the recorded data structure, indicating that the system was not designed to capture, store, or propagate measurement uncertainty information.

## B. Metrological Analysis and Framework Derivation

Following problem identification, a metrological analysis was conducted to establish the formal relationship between the observed operational parameters and internationally recognized uncertainty frameworks.

The 0.2% maximum permissible error applied as the calibration standard for dosing weighers was examined within the context of OIML weighing instrument classification [2]. As established in weighing instrument practice, the relative measurement uncertainty of a weighing instrument follows a hyperbolic relationship with applied load — it does not remain constant across the weighing range but increases disproportionately as the measured quantity decreases relative to the instrument's capacity [6]. Consequently, MPE represents not merely a pass/fail calibration threshold, but a parameter connected to the actual measurement uncertainty of each individual weighing event. For a weigher operating with a 0.2% MPE, the associated measurement uncertainty applicable to any weighing event is proportional to the load present on the weighing platform at the time of measurement — not to the delivered ingredient weight alone.

This derivation reveals a critical distinction in how the uncertainty factor is applied within sequential cumulative dosing systems. Because each ingredient is dosed onto an already-loaded platform, the load present at the time of measurement is not the delivered ingredient weight alone, but the accumulated gross weight of all previously dosed ingredients combined with the current ingredient. Consequently, the effective uncertainty associated with each dosing event is proportional to the accumulated platform weight, not to the individual ingredient quantity reported in the dosing record.

This finding provides a metrological basis for the minimum dosing limits observed in practice. When an ingredient quantity represents a sufficiently small fraction of the accumulated platform weight, the associated uncertainty may approach or exceed the allowable formula tolerance for that ingredient — rendering the dosing result metrologically unreliable despite appearing acceptable in the computerized report. The minimum dosing limits of 2% for macro ingredients and 4% for micro ingredients can therefore be understood as practical approximations of the threshold below which this condition occurs, consistent with the minimum weight concept described in weighing instrument practice [6].

The analysis further identifies that this uncertainty is neither evaluated nor recorded at the individual dosing event level within the observed SCADA implementation. As a result, cumulative uncertainty cannot be reconstructed from existing manufacturing records, consistent with the structural gap identified in Section A.

The metrological framework derived from this analysis forms the basis for the conceptual proposal presented in Section IV.

### C. Conceptual Framework Development

Building on the metrological derivation presented in Section B, a GUM-consistent conceptual framework is proposed for sequential cumulative dosing systems [3], [4]. The framework addresses four interconnected elements: the evaluation of measurement uncertainty at each individual dosing event based on instrument characteristics and operating conditions; the propagation of uncertainty through the cumulative dosing sequence; the integration of uncertainty information into SCADA dosing records at the point of measurement; and the presentation of uncertainty information within both detail batch reports and aggregated production reports.

The framework establishes a metrological structure through which uncertainty information can be preserved throughout the measurement lifecycle, from individual dosing events to manufacturing reports. Particular attention is given to uncertainty sources relevant to industrial dosing systems, including instrument resolution, linearity effects, environmental influences, and dosing algorithm behavior. By identifying these sources and their points of interaction within the measurement process, the framework provides a basis for uncertainty-aware manufacturing reporting.

This paper presents the framework at a conceptual level and focuses on establishing the metrological need for uncertainty integration within SCADA-based sequential cumulative dosing systems. The detailed mathematical formulation of uncertainty evaluation and propagation, experimental validation of the proposed approach, and implementation within industrial SCADA environments are identified as directions for future research.

## Results and Discussion

### From Load Cells to Database.

Before discussing the main topic of measurement uncertainty in sequential cumulative weighing systems, it is important to briefly review how weighing data are generated and transferred within computerized dosing systems.

In industrial weighing systems, load cells are commonly used to convert applied mass into low-level electrical signals, typically in the microvolt range. These signals are subsequently amplified, processed, and interpreted by digital weighing indicators [2].

In the system under study, digital indicators communicate with programmable logic controllers (PLCs) through various communication methods, including analog signals, digital I/O, serial communication, or Ethernet-based protocols. The PLC records ingredient weight data within internal registers throughout the dosing process. After completion of a dosing batch, the recorded data are commonly transferred to computer systems or databases for report generation and production tracking purposes.

In some PC-based architectures, the computer system may directly communicate with digital weighing indicators and control the process through remote I/O systems without intermediary PLC processing.

Throughout this measurement and communication chain, multiple stages of signal conversion, transmission, and data interpretation may exist between the original physical mass and the final computerized report representation. Depending on system architecture and implementation quality, inaccuracies or signal interpretation deviations may potentially occur at several stages within the data acquisition process.

The use of digital load cells and fully digital communication methods, such as serial or Ethernet-based communication protocols, may reduce potential signal conversion errors compared to analog transmission methods.

Modern dosing systems increasingly utilize fully digital Ethernet-based communication architectures, reducing potential signal conversion and transmission errors. However, in older industrial systems, analog transmission between digital weighing indicators and PLC analog input modules may still be used. In such configurations, additional uncertainty may arise from analog-to-digital conversion, signal scaling, electrical interference, and calibration inconsistencies within the measurement chain.

## The Uncertainty in Concrete Number

The following report was extracted from the production system under investigation. It is a real example of a dosing report generated for a production batch. To protect the company's intellectual property, material names have been anonymized, and the Req. and Dlv. values have been slightly modified. However, the modifications were intentionally limited so that the proportional relationship between deviation and tolerance remained unchanged.

The same type of uncertainty-related issue discussed later in this paper exists within this actual production report example (all weight is in kg).

| Material Name | Weigher | REQ | DLV | DEV | TOL | TL | TM |
|---|---|---|---|---|---|---|---|
| Material A | W1 | 122 | 121 | 1 | 4 | 0 | 0 |
| Material B | W1 | 872 | 872 | 0 | 5 | 0 | 0 |
| Material C | W1 | 118 | 120 | -2 | 2 | 0 | 0 |
| Material D | W1 | 118 | 117 | 1 | 2 | 0 | 0 |
| Material E | W1 | 132 | 133 | -1 | 2 | 0 | 0 |
| Material F | W2 | 363 | 362 | 1 | 2 | 0 | 0 |
| Material G | W2 | 329 | 329 | 0 | 2 | 0 | 0 |
| Material H | W2 | 240 | 241 | -1 | 5 | 0 | 0 |

Weigher = Dosing Weigher

Req. = Requested amount by Formula.

Dlv. = Recorded delivered amount by the computer system.

Dev. = Deviation/difference between Requested and Recorded Delivery (Dev = Req - Dlv).

Tol. = Allowed tolerance by system. Often smaller than the allowed tolerance by formula.

TM = Time Alarm number throughout the process.

TL = Tolerance Alarm throughout the process.

At first glance, the computerized dosing report shown above appears to provide precise and reliable information regarding ingredient delivery accuracy. Each ingredient is represented by exact numerical values, including requested quantity, delivered quantity, deviation, and tolerance status.

Operationally, ingredients with delivery differences remaining within the configured tolerance limits are generally interpreted as successfully dosed materials. However, this kind of report hides uncertainty, and in sequential cumulative weighing systems this uncertainty could become bigger than the applied tolerance can accommodate.

### First Source of Uncertainty: Digital Weigher Resolution

Digital weighing systems present measurement results as clean and definite numerical values. At first glance, such representation appears to eliminate reading ambiguity commonly associated with analog instruments, such as parallax error. However, digital weighing systems still possess inherent limitations, one of the most fundamental being measurement resolution.

In digital weighing systems, resolution refers to the smallest increment — referred to as the scale interval d — by which the displayed measurement value can change [2]. In the dosing system under investigation, macro ingredient weighers operate with a display resolution of 1 kg, meaning measurements are presented in discrete 1 kg increments.

As a consequence, every displayed measurement inherently contains uncertainty associated with the resolution limit itself [3]. The displayed value does not necessarily represent the exact physical mass, but rather the nearest representable increment permitted by the system resolution. Under GUM conventions, resolution contributes a Type B uncertainty component evaluated as a rectangular distribution with standard uncertainty [3]:

$u(res) = d / (2\sqrt{3})$

For the dosing weighers under investigation, where $d = 1$ kg:

$u(res) = 1 / (2\sqrt{3}) = 0.289$ kg

Applying a coverage factor k = 2 for approximately 95% confidence, the expanded uncertainty attributable to resolution alone is:

U(res) = 2 × 0.289 = ±0.577 kg

This value is present in every dosing event, for every ingredient, regardless of dosed quantity or accumulated platform load. It is invisible in the computerized dosing report, as no uncertainty information is recorded alongside the delivered weight values.

In the dosing report extracted from the system under investigation, Material C shows a recorded deviation of -2 kg within an allowed tolerance of ±2 kg — with no tolerance alarm triggered (TL=0), and therefore interpreted operationally as a successful dosing event. However, applying the resolution uncertainty derived above, the actual physical deviation corresponding to the displayed value may exist within the range:

-2 ± 0.577 kg = -2.577 kg to -1.423 kg

The lower bound of this range, -2.577 kg, already exceeds the allowed tolerance of ±2 kg. Material C therefore cannot be confirmed as compliant from the dosing report alone — a conclusion that is entirely invisible within the current reporting system.

This finding is based on resolution uncertainty only, representing a single uncertainty source. The following section introduces a second, structurally more significant source of uncertainty inherent to sequential cumulative dosing systems — one that grows with each successive dosing event and cannot be recovered from existing production records.

### Second Source of Uncertainty: Dosing System Repeatability

In addition to resolution limitations, digital dosing systems introduce a second source of uncertainty arising from the interaction between dosing algorithm behavior and actual manufacturing conditions.

In industrial dosing systems, a typical dosing sequence involves waiting for a stable empty platform reading, initiating material feed toward a target weight adjusted by inflight correction, waiting for a stable delivered weight reading, and recording the measurement result before proceeding to the next ingredient. The accuracy and consistency of this process depends not only on instrument characteristics, but also on the stability evaluation method implemented within the dosing algorithm and the real-time environmental conditions present during operation.

Factors such as machine vibration, airflow disturbances, pneumatic pressure fluctuations, and mechanical resonance may influence weighing stability during the dosing process. Dosing algorithms must therefore balance measurement stability against production throughput requirements — a compromise that introduces process-induced variability into the delivered weight values recorded by the system.

Under GUM conventions, repeatability is evaluated as a Type A uncertainty component, derived from repeated observations of the dosing process under nominally identical conditions [3]:

$$u(\text{rep}) = s / \sqrt{n}$$

where $s$ is the experimental standard deviation of repeated delivered weight measurements and $n$ is the number of observations.

Repeatability testing was conducted across several dosing weighers within the facility under investigation. Due to practical constraints, direct repeatability testing on the primary macro dosing weighers was not available at the time of this study. The repeatability uncertainty value applied here was therefore derived from testing conducted on a comparable dosing weigher within the same facility, using the highest observed standard deviation across available test data as a conservative estimate. Due to confidentiality requirements, the full test reports cannot be included in this publication; however, the derived uncertainty value is applied in the combined uncertainty evaluation presented in this study.

From the most conservative repeatability test available, the standard deviation of delivered weight measurements was $s = 0.111$ kg across $n = 5$ repeated observations, yielding:

$$u(\text{rep}) = 0.111 / \sqrt{5} = 0.050 \text{ kg}$$

Like resolution uncertainty, repeatability uncertainty does not vary with accumulated platform load. It reflects the consistent behavioral characteristics of the dosing algorithm and process environment, contributing a fixed uncertainty component to every dosing event regardless of ingredient sequence or platform load condition.

The expanded repeatability uncertainty at $k = 2$ is:

$$U(\text{rep}) = 2 \times 0.050 = \pm 0.100 \text{ kg}$$

### Combined Uncertainty: Sources 1 and 2

With two independent, fixed uncertainty components now established, the combined standard uncertainty from resolution and repeatability can be evaluated using the GUM law of propagation of uncertainty [3]:

$u(c1,2) = \sqrt{(u(res)^2 + u(rep)^2)}$

$= \sqrt{(0.289^2 + 0.050^2)}$

$= \sqrt{(0.0835 + 0.0025)}$

$= \sqrt{0.0860}$

$= 0.293$ kg

The corresponding expanded combined uncertainty at $k = 2$ is:

$U(c1,2) = 2 \times 0.293 = \pm 0.587$ kg

This value represents the baseline uncertainty present in every dosing event, attributable solely to instrument resolution and process repeatability — both of which are constant regardless of ingredient sequence or accumulated platform load. In this particular example, resolution dominates the combined figure, contributing 0.289 kg of the 0.293 kg standard uncertainty total, with repeatability contributing only marginally.

This relationship, however, is not universal. Depending on environmental conditions, mechanical design, installation quality, and dosing algorithm implementation, repeatability uncertainty may equal or exceed resolution uncertainty in other weigher configurations or operating environments. The specific proportion between the two sources will vary by system. The fundamental point remains: combining two independent uncertainty sources always results in a larger combined uncertainty than either source alone — and neither source is visible in the computerized dosing report.

Returning to Material C from the dosing report under investigation — REQ = 118 kg, DLV = 120 kg, DEV = -2 kg, TOL = ±2 kg — the expanded combined uncertainty from Sources 1 and 2 alone places the actual deviation within the range:

$-2 \pm 0.587$ kg $= -2.587$ kg to $-1.413$ kg

The lower bound of -2.587 kg exceeds the allowed tolerance of ±2 kg. Material C therefore cannot be confirmed as compliant based on these two uncertainty sources alone — before the third and most structurally significant source is introduced.

## Third Source of Uncertainty: Accumulated Platform Load in Sequential Cumulative Dosing

The first two sources of uncertainty — resolution and repeatability — are fixed components that remain constant regardless of ingredient sequence or platform load condition. The third source of uncertainty is fundamentally different in nature: it grows with each successive dosing event and is structurally inherent to sequential cumulative dosing systems.

### Load Cell Physics and the Nature of MPE

In industrial weighing systems, load cells function as measuring transducers that produce an electrical output signal in response to the total force applied to the load receptor [2]. This output signal represents the entire load present on the platform at the time of measurement — it cannot distinguish between previously accumulated material and the ingredient currently being dosed. The weighing indicator converts this total signal into a displayed weight value, from which the delivered ingredient weight is inferred by the dosing system as the difference between the current and previous platform readings.

The maximum permissible error of a dosing weigher is defined as a proportion of the load — expressed as 0.2% in the system under investigation. This proportional nature means that the absolute permissible error band is not constant but widens linearly with increasing platform load. At 200 kg platform load, the permissible error is ±0.4 kg. At 500 kg, it is ±1.0 kg. At 1,000 kg, it is ±2.0 kg. At 2,000 kg, it reaches ±4.0 kg.

This behavior is consistent with load cell operating principles, in which signal output is proportional to total applied load, and has been consistently observed across dosing weigher installations throughout the author's 25 years of professional experience in industrial feed manufacturing automation. It is further consistent with the characterization of relative MPE behavior described in weighing instrument practice, where the absolute error tolerance scales linearly with the measured load [2][6].

### *The Misapplication in Sequential Cumulative Dosing*

In a sequential cumulative dosing system, each ingredient is dosed onto a platform that already carries the accumulated weight of all previously dosed ingredients. At the moment each dosing event is measured, the load cell output — and therefore the measurement uncertainty — is proportional to the total accumulated platform load, not to the individual ingredient weight being delivered.

This distinction is critical. The dosing report records only the delivered ingredient weight and evaluates its deviation against a fixed tolerance. It does not account for the fact that the uncertainty associated with that measurement is governed by the total platform load at the time of measurement. As the dosing sequence progresses and the platform load increases, the uncertainty associated with each successive dosing event grows — yet the report applies identical tolerance evaluation to every ingredient regardless of its position in the dosing sequence.

This represents a structural misapplication of tolerance evaluation in sequential cumulative dosing systems: the uncertainty grows with each dosing event, but the reporting system treats all events as metrologically equivalent.

Quantification: Applying MPE-Derived Uncertainty to Material C

Returning to the dosing report under investigation, the dosing sequence on Weigher W1 proceeds as follows:

| Ingredient | Delivered (kg) | Accumulated Platform Load (kg) |
|---|---:|---:|
| Material A | 121 | 121 |
| Material B | 872 | 993 |
| Material C | 120 | 1,113 |

At the moment Material C is dosed, the platform carries an accumulated load of 993 kg from Materials A and B. The total platform load at the completion of Material C dosing is approximately 1,113 kg.

Applying the 0.2% MPE to the accumulated platform load at the time of Material C measurement:

u(load) = 0.2% × 1,113 = 2.226 kg

This uncertainty component alone already exceeds the allowed tolerance of ±2 kg for Material C. Unlike the resolution and repeatability components derived previously, this uncertainty is not fixed — it is specific to Material C's position in the dosing sequence and the accumulated load present at that moment.

## Combined Uncertainty: All Three Sources

With all three independent uncertainty sources now established, the combined standard uncertainty for Material C is evaluated using the GUM law of propagation of uncertainty [3]:

$$u(\text{combined}) = \sqrt{u(\text{res})^2 + u(\text{rep})^2 + u(\text{load})^2}$$

$$= \sqrt{0.289^2 + 0.050^2 + 2.226^2}$$

$$= \sqrt{0.0835 + 0.0025 + 4.955}$$

$$= \sqrt{5.041}$$

$$= 2.245 \text{ kg}$$

The expanded combined uncertainty at $k = 2$ is:

$$U(\text{combined}) = 2 \times 2.245 = \pm 4.490 \text{ kg}$$

Applying this to Material C's recorded deviation of -2 kg:

$$\text{Actual deviation range} = -2 \pm 4.490 \text{ kg} = -6.490 \text{ kg to } +2.490 \text{ kg}$$

The dosing report records Material C as compliant — deviation -2 kg within tolerance ±2 kg, no alarm triggered. The combined uncertainty evaluation reveals that the actual delivered quantity may deviate from the requested amount by up to ±4.490 kg, a range more than twice the allowed tolerance. This result is entirely invisible in the computerized dosing report.

## The Progressive Nature of Platform Load Uncertainty: Materials D and E

The uncertainty associated with platform load does not stop at Material C. As the dosing sequence continues on Weigher W1, Materials D and E are dosed onto an already heavily loaded platform, carrying progressively larger load-dependent uncertainty components.

| Ingredient | Delivered (kg) | Accumulated Load (kg) | u(load) (kg) | u(combined) (kg) | U (±kg) | DEV (kg) | TOL (±kg) | Actual Range (kg) |
|---|---|---|---|---|---|---|---|---|
| Material A | 121 | 121 | 0.242 | 0.364 | 0.728 | 1 | 4 | 0.272 to 1.728 |
| Material B | 872 | 993 | 1.986 | 1.997 | 3.994 | 0 | 5 | -3.994 to +3.994 |
| Material C | 120 | 1,113 | 2.226 | 2.245 | 4.49 | -2 | 2 | -6.490 to +2.490 |
| Material D | 117 | 1,230 | 2.46 | 2.478 | 4.955 | 1 | 2 | -3.955 to +5.955 |
| Material E | 133 | 1,363 | 2.726 | 2.742 | 5.483 | -1 | 2 | -6.483 to +4.483 |

Material D: REQ=118, DLV=117, DEV=1, TOL=±2

At the moment Material D is dosed, the platform carries 1,230 kg. Applying 0.2% MPE:

u(load) = 0.2% × 1,230 = 2.460 kg

u(combined) = $\sqrt{(0.289^2 + 0.050^2 + 2.460^2)} = \sqrt{6.138} = 2.478$ kg

U(combined) = 2 × 2.478 = ±4.955 kg

Actual deviation range = 1 ± 4.955 = -3.955 kg to +5.955 kg

Reported as compliant. Cannot be confirmed as compliant.

Material E: REQ=132, DLV=133, DEV=-1, TOL=±2

At the moment Material E is dosed, the platform carries 1,363 kg. Applying 0.2% MPE:

u(load) = 0.2% × 1,363 = 2.726 kg

u(combined) = $\sqrt{(0.289^2 + 0.050^2 + 2.726^2)} = \sqrt{7.517} = 2.742$ kg

U(combined) = 2 × 2.742 = ±5.483 kg

Actual deviation range = -1 ± 5.483 = -6.483 kg to +4.483 kg

Reported as compliant. Cannot be confirmed as compliant.

The pattern is unambiguous: as the dosing sequence progresses and the accumulated platform load increases, the expanded uncertainty grows with each successive ingredient. Materials C, D, and E — all reported as compliant with no tolerance alarms — cannot be confirmed as compliant once measurement uncertainty is properly accounted for. The dosing report presents five ingredients on W1 as successfully dosed. The uncertainty analysis reveals that three of them are metrologically unverifiable from the report alone.

This cascading effect is unique to sequential cumulative dosing systems. It does not arise in single-event weighing applications, and it cannot be detected, quantified, or reported by a SCADA implementation that records only delivered weight values without an embedded uncertainty model — consistent with the structural gap identified in Section III.

### Reference Chain Uncertainty in Sequential Cumulative Dosing

Beyond the uncertainty associated with accumulated platform load, sequential cumulative dosing systems introduce an additional and structurally distinct source of uncertainty — one that arises from the nature of how each ingredient's delivered weight is determined.

In a sequential cumulative dosing system, the delivered weight of each ingredient is not measured directly as an isolated quantity. Instead, it is calculated as the difference between two successive platform readings: the reading captured immediately after the current ingredient stabilizes, and the reference reading captured immediately before dosing of that ingredient began. This reference reading represents the accumulated platform load from all previously dosed ingredients.

Both readings — the reference before dosing and the final reading after dosing — contain their own measurement uncertainty, arising from resolution, repeatability, and platform load conditions at the time each reading is taken. Under GUM conventions, when a quantity is determined as the difference between two uncertain measurements, the uncertainty of both input readings propagates into the derived result [3]:

$$u(\text{Delivered}) = \sqrt{u(\text{reading after})^2 + u(\text{reading before})^2}$$

This formulation reveals that the uncertainty of each ingredient's delivered weight is not determined by the final platform load alone, but by the combined uncertainty of two successive platform readings — each evaluated at their respective load conditions at the time of capture.

Which means, the complete uncertainty at ingredients two and above, are growing significantly greater than previous uncertainty calculation.

To illustrate this, consider Material C from the table above. Under the correct metrological treatment, its delivered weight is determined by two platform readings: the reference reading at 993 kg immediately before dosing begins, and the final reading at 1,113 kg when dosing completes. Each reading carries its own load-proportional uncertainty. At 993 kg, u(ref) = 1.997 kg; at 1,113 kg, u(load) = 2.245 kg. The combined uncertainty of Material C's delivered weight is therefore:

$u(\text{combined}) = \sqrt{(1.997^2 + 2.245^2)} = \sqrt{(3.988 + 5.04)} = \sqrt{9.028} = 3.004$ kg

$U(\text{combined}) = 2 \times 3.004 = \pm 6.008$ kg

This is notably larger than the ±4.490 kg reported in the preceding section, which accounted only for the final reading uncertainty. The difference — 1.518 kg — represents the contribution of the reference reading uncertainty, silently omitted from the original calculation.

Applying this correction across the full dosing sequence yields the following revised uncertainty values:

| Ingredient | Delivered (kg) | Accumulated Load (kg) | u(ref. combined) (kg) | u(acc. combined) (kg) | u(ref + acc) (kg) | U (±kg) | DEV (kg) | TOL (±kg) | Actual Range (kg) |
|---|---|---|---|---|---|---|---|---|---|
| Material A | 121 | 121 | 0 | 0.364 | 0.364 | 0.728 | 1 | 4 | 0.272 to 1.728 |
| Material B | 872 | 993 | 0.364 | 1.997 | 2.03 | 4.059 | 0 | 5 | -4.059 to +4.059 |
| Material C | 120 | 1,113 | 1.997 | 2.245 | 3.005 | 6.009 | -2 | 2 | -8.009 to +4.009 |
| Material D | 117 | 1,230 | 2.245 | 2.478 | 3.344 | 6.688 | 1 | 2 | -5.688 to +7.688 |
| Material E | 133 | 1,363 | 2.478 | 2.742 | 3.696 | 7.392 | -1 | 2 | -8.392 to +6.392 |

From Material B onward, every ingredient faces exactly two uncertainty sources — its reference reading and its final reading. The uncertainty does not compound indefinitely through the sequence; each ingredient's evaluation resets at its own reference reading. However, because both readings are taken at progressively higher platform loads, the combined uncertainty grows systematically with each successive ingredient — reaching ±7.392 kg for Material E, against a tolerance of ±2 kg.

### *Implications for Reporting and Traceability*

This distinction has significant implications for manufacturing report interpretation. A dosing report that appears to present precise delivered weight values for each ingredient is, in the absence of recorded reference uncertainties, presenting quantities whose metrological basis cannot be fully reconstructed. The delivered weight of each ingredient is a derived quantity — a difference between two uncertain readings — and without both readings preserved with their associated uncertainties, the uncertainty of the derived quantity cannot be determined from the report alone [3][4].

This condition is consistent with the data completeness requirement established in OIML R 61-1 Section 5.9, which specifies that stored measurement data shall contain all relevant information necessary to reconstruct an earlier measurement [2]. In the system under investigation, the absence of reference reading uncertainty from the recorded data structure means this reconstruction requirement cannot be satisfied for any ingredient beyond the first in a dosing sequence.

The practical consequence is that the longer the dosing sequence and the heavier the accumulated platform load, the less recoverable the uncertainty of individual ingredient deliveries becomes from the printed report alone — yet the report presents all delivered quantities with identical implied precision regardless of their position in the sequence.

## Loss of Uncertainty Traceability in Aggregated Reports

The preceding analysis addressed measurement uncertainty in the context of individual batch dosing records and formula compliance. A separate but equally significant problem arises at the level of aggregated manufacturing reports, where the operational consequences of unmodeled uncertainty manifest in a different context — one affecting inventory management, material reconciliation, cost calculation, and overall manufacturing performance assessment.

Within practical manufacturing operations, detailed batch dosing reports are commonly reviewed primarily by production and quality control personnel, particularly when quality anomalies or process deviations are detected. Other operational departments — including warehouse management, accounting, finance, and managerial functions — typically rely more heavily on aggregated manufacturing reports rather than individual batch-level dosing records. Common examples include total raw material usage per recipe, total raw material consumption across production periods, and total finished product output.

Finished product reporting may often be cross-verified against bagging machine output records, allowing relatively direct estimation of production quantity and material shrinkage. Raw material consumption reporting, however, relies much more heavily on computerized dosing data derived directly from the sequential cumulative weighing process. At the aggregated reporting level, delivered material quantities are represented only as accumulated totals, with no visibility into individual dosing sequences, batch-level weighing conditions, or the sequence-dependent uncertainty associated with each dosing event.

As a consequence, the information required to reconstruct effective measurement uncertainty is no longer available within the aggregated report structure [2]. The original accumulated platform load conditions, ingredient sequence positions, and uncertainty states associated with each dosing event cannot be traced from summarized consumption figures alone. While a rough generalized uncertainty estimate may still be possible, the sequence-dependent nature of uncertainty in sequential cumulative dosing systems means that a single uniform error margin applied across all materials becomes metrologically misleading [3].

This problem is compounded within total raw material usage reports, where materials originating from different dosing sequences, different weighing conditions, and different accumulated platform load states are combined into single summarized consumption values. The uncertainty associated with early-sequence ingredients — dosed onto lightly loaded platforms — differs fundamentally from that of late-sequence ingredients dosed onto heavily accumulated platforms. Aggregating these into a single figure without uncertainty weighting produces a consumption report whose implied precision cannot be supported by the underlying measurement process [5].

The practical consequence is that aggregated manufacturing reports may be used to assess material shrinkage, reconcile inventory, or evaluate production efficiency against targets — while the uncertainty embedded in the underlying dosing data remains unquantified and invisible. As

Imkamp et al. observe, a complete measurement result requires the best estimate of the measured value, its unit, and the associated measurement uncertainty [5]. Aggregated production reports as currently structured satisfy only the first two requirements, presenting consumption figures as deterministic quantities with a level of implied certainty that exceeds the actual metrological traceability of the dosing process [2][7].

This represents a structural limitation of the current reporting architecture — not an operational error, but a consequence of the absence of an embedded uncertainty model within the SCADA implementation. Without uncertainty information recorded at the individual dosing event level, it cannot be propagated, aggregated, or presented at any higher reporting level, regardless of the sophistication of the reporting system built above it [3][4].

### Proposed Solution

The analysis presented in this study indicates that the fundamental cause of the identified reporting problem is the absence of an embedded measurement uncertainty model within the SCADA architecture that is investigated in this study. While the dosing system records weight values throughout the manufacturing process, it lacks the capability to evaluate, store, propagate, and report the uncertainty associated with those measurements. Consequently, uncertainty information is lost at the point of measurement and cannot be reconstructed from historical production records.

To address this limitation, a conceptual framework is proposed in which measurement uncertainty is treated as an integral process parameter rather than as a calibration-related attribute existing outside the manufacturing information system. The framework is based on a hybrid uncertainty evaluation approach combining multiple uncertainty contributors relevant to industrial dosing systems.

First, uncertainty associated with instrument resolution is incorporated as a Type B uncertainty component. Resolution represents an inherent limitation of the measurement system and contributes directly to the uncertainty of every dosing event [4].

Second, uncertainty associated with operational performance is evaluated through statistical analysis of dosing accuracy under normal operating conditions. This component encompasses factors such as dosing algorithm performance, process variability, and other operational influences affecting the ability of the system to achieve the requested target weight. Because these effects are derived from observed system behavior, they constitute a Type A uncertainty contribution [4].

Future implementations may incorporate automated estimation of operational uncertainty through the plant SCADA system. By periodically collecting verification measurements and maintaining a historical record of dosing performance, the statistical component of uncertainty could be continuously updated using current operational data. Such an approach would provide a dynamic estimate of Type A uncertainty that reflects the actual performance of the dosing system, rather than relying solely on infrequent studies or historical evaluations. This concept is consistent with emerging Industry 4.0 approaches in manufacturing metrology, where measurement systems increasingly incorporate continuous performance monitoring and automated assessment of measurement quality [5].

Third, uncertainty associated with load-dependent instrument behavior is evaluated through periodic calibration and verification activities conducted at multiple points throughout the weighing range [2], [7]. By characterizing instrument performance at incremental percentages of capacity, a load-dependent uncertainty function can be established, allowing uncertainty to be evaluated as a function of accumulated platform weight rather than as a single constant value. The combination of these uncertainty contributors enables each dosing weigher to be associated with a quantified expanded uncertainty appropriate to its operating condition [3], [4]. Once available, this information can support several functions within the manufacturing process.

The first application is the evaluation of compatibility between a dosing system and a production formula. A dosing system should be capable of achieving uncertainty levels that remain acceptable relative to the tolerance requirements of all ingredients within the formula. In sequential cumulative dosing systems, this assessment must consider not only the requested quantity of an ingredient, but also its position within the dosing sequence, since accumulated platform weight may influence the uncertainty associated with a given dosing event.

The second application is uncertainty-aware process execution. During automatic dosing, uncertainty information can be evaluated and propagated throughout the cumulative batching sequence, allowing each dosing event to be recorded together with its associated uncertainty. In this manner, uncertainty becomes a traceable characteristic of the manufacturing process rather than an external assumption applied after production has been completed [5].

The third application is uncertainty-aware manufacturing reporting. By incorporating uncertainty information into both detailed batch records and aggregated production reports, manufacturing data can be presented in a form that more accurately reflects the metrological capability of the underlying measurement system. Such reporting improves transparency and reduces the risk of false interpretation arising from deterministic presentation of inherently uncertain measurement results [5].

The implementation of uncertainty-aware dosing presents significant practical challenges. In sequential cumulative dosing systems, uncertainty depends not only on ingredient quantity but also on cumulative platform load, dosing sequence, and instrument operating condition. As a result, manual evaluation and application of uncertainty information would be impractical in routine manufacturing operations.

For this reason, the proposed framework recommends that uncertainty evaluation, propagation, recording, and reporting be incorporated directly into SCADA functionality. By embedding uncertainty calculations within the system architecture, uncertainty information can be generated automatically at the point of measurement, propagated throughout the cumulative dosing process, and preserved within manufacturing records without imposing additional operational burden on users [4].

Such integration would transform measurement uncertainty from a calibration-related concept into an operational parameter available throughout production planning, dosing execution, and manufacturing report interpretation [5].

## Conclusion

Measurement uncertainty is a fundamental component of a complete measurement result [3][5]. However, uncertainty information is generally absent from SCADA-based sequential cumulative dosing systems, where only deterministic weight values are recorded, processed, and reported. As a result, manufacturing reports present dosing outcomes with an apparent level of precision that cannot be fully supported by the underlying measurement system.

This study identified a metrological consequence that is unique to sequential cumulative dosing systems. Unlike isolated weighing operations, individual dosing events in a sequential dosing process are not independent measurements. Each dosing event contributes to an accumulated platform weight that serves as the reference condition for subsequent dosing operations. Consequently, when uncertainty is not evaluated and recorded at individual dosing events, the omission propagates throughout the cumulative batching sequence. By the time manufacturing data are compiled into batch histories and aggregated production reports, the uncertainty associated with the process can no longer be reconstructed from the recorded data.

Through field observation, practitioner inquiry, and literature analysis, this study demonstrated that current reporting practices provide no mechanism for evaluating, storing, propagating, or reporting measurement uncertainty within the dosing process. The analysis further showed that long-established operational parameters, including maximum permissible error requirements and minimum dosing limits, can be interpreted within a common metrological framework based on measurement uncertainty, providing a previously undocumented explanation for their practical application.

To address the identified gap, a GUM-consistent conceptual framework [3], [4] was proposed in which uncertainty is evaluated at individual dosing events, and preserved throughout the cumulative dosing process, enabling uncertainty information to remain associated with manufacturing data from measurement through reporting[5].

The principal contribution of this work is the identification of uncertainty propagation as an inherent metrological challenge in sequential cumulative dosing systems and the establishment of a conceptual framework through which that challenge can be addressed. Future research should focus on the development of quantitative uncertainty models, experimental validation using industrial data, and implementation of uncertainty-aware functionality within operational SCADA environments.

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