A Structured Framework for Measurement Uncertainty in Bulk Gain-in-Weight Batching Systems in Feed Manufacturing SCADA

Abstract

Bulk Gain-In-Weight (GIW) batching systems present a metrological challenge absent from isolated weighing operations.

When multiple ingredients are dosed sequentially onto a single weighing platform, each measurement is taken against an accumulated platform load rather than an empty reference. The uncertainty associated with each dosing event is therefore not dependent on the delivered ingredient weight, but on the total accumulated load at the time of measurement — and grows with each successive ingredient in the sequence.

Current SCADA implementations for bulk GIW batching are not known to incorporate an explicit measurement uncertainty model.

Without it, two critical operational functions are absent: pre-dosing feasibility assessment, which would identify whether a formula's ingredients are compatible with the weigher's metrological capability before production begins, and process-level uncertainty tagging, which would enable metrologically complete batch histories and support reliable aggregated reporting.

This paper identifies this architectural absence as the core problem and proposes a GUM-consistent conceptual framework to address it.

The framework defines uncertainty evaluation from instrument resolution, process repeatability, and accumulated platform load; propagates uncertainty through the cumulative batching sequence; and integrates it into SCADA architecture to support both operational functions.

Field observation, practitioner inquiry, and analysis of a hypothetical feed formulation demonstrate that uncertainty in Bulk GIW batching increases with accumulated platform load and successive weighing operations. Consequently, later dosing events may exhibit uncertainty exceeding both ingredient tolerance limits and the uncertainty of a single weighing result at maximum scale capacity.

Keywords:

Measurement Uncertainty, Bulk Gain-In-Weight Batching System, Uncertainty Propagation, SCADA, Dosing, Industrial Weighing, Feed Manufacturing

1. Introduction

Animal feed manufacturing relies on precise ingredient dosing to ensure product consistency, nutritional compliance, and process efficiency.

In modern feed mills, dosing operations are typically controlled and recorded by Supervisory Control and Data Acquisition (SCADA) systems. A common configuration is the bulk GIW batching system, in which multiple ingredients are weighed and accumulated sequentially within a single batch receiver. The resulting measurement records form the basis for production control, quality verification, regulatory compliance, and historical manufacturing reports [1, 2].

These records typically include target weights, actual weights, tolerances, timestamps, operator information, and traceability data; however, measurement uncertainty is generally not represented as a reported process variable. For isolated weighing operations, uncertainty information can often be obtained separately from instrument calibration and verification records because each reported value corresponds directly to a single weighing event. Bulk GIW batching, however, presents a metrological characteristic that distinguishes it from isolated weighing operations.

Each ingredient is dosed onto a platform that already carries the accumulated weight of all previously dosed ingredients. At the moment of measurement, the load cell responds to the total accumulated platform load — not to the delivered ingredient weight alone. Consequently, the uncertainty associated with each dosing event is dependent on the accumulated platform load at the time of measurement and grows with each successive ingredient in the sequence. This behavior is inherent to the system architecture.

Despite this characteristic, current SCADA implementations for bulk GIW batching are not known to incorporate an explicit measurement uncertainty model. The absence of such a model creates a gap at two points in the manufacturing process.

Before production begins, the system cannot evaluate whether a formula's ingredients are compatible with the metrological capability of the assigned weighers — a feasibility assessment that must account not only for requested ingredient quantities, but also for their positions within the dosing sequence.

Implementing uncertainty based on weigher capacity uniformly across all ingredients preserves reliability but unnecessarily restricts operational flexibility. Implementing it based solely on requested ingredient quantity improves flexibility but underestimates actual uncertainty for later ingredients in the sequence — where accumulated platform load dominates. In current practice, the former approach is typically adopted — applying maximum uncertainty uniformly to maintain reliability at the cost of flexibility.

During and after production, uncertainty is neither evaluated at individual dosing events nor propagated through the cumulative sequence, leaving manufacturing records without the information required to assess, reconstruct, or report metrological traceability.

Although measurement uncertainty is recognized as an essential component of a complete measurement result [6, 7], neither current regulatory frameworks nor industry reporting standards require its inclusion in batch production records [1, 2]. The dosing reports examined in this study conform fully to established requirements. The gap identified here is therefore not a deviation from standard practice — it is a structural absence at the level of the standards and systems themselves.

This paper identifies the missing uncertainty model as the root architectural problem and proposes a GUM-consistent conceptual framework to address it [6, 7]. The framework defines uncertainty evaluation at individual dosing events from instrument resolution, process repeatability, and accumulated platform load; propagates uncertainty through the GIW batching’s dosing sequence; and integrates uncertainty information into SCADA architecture to support pre-dosing feasibility assessment and process-level uncertainty tagging throughout manufacturing records.

To evaluate whether the identified uncertainty gap carries practical significance, this paper attempts to quantify uncertainty through a representative hypothetical scenario modeled on several OIML R76 Class III, and benchmarks the results against the allowed deviation defined by Kansas State University Feed Manufacturing Guide.

The remainder of this paper is organized as follows. Section 2 reviews relevant literature. Section 3 identifies the research gap. Section 4 presents the methodology and proposed framework. Section 5 presents results and discussion. Section 6 presents conclusions.

2. Literature Review

2.1. 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 [6]. 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 [6].

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 [6].

Legal metrology frameworks establish maximum permissible errors (MPE) as the basis for instrument verification and calibration acceptance criteria. OIML R 76-1 governs non-automatic weighing instruments and establishes that MPE is not a fixed value but varies with applied load — expressed as multiples of the verification scale interval e across defined load thresholds [4]. For a graduated instrument without auxiliary indicating device, the verification scale interval e is equal to the actual scale interval d, as established in R 76-1 Section 3.1.2 [4]. For Class III instruments — the class applicable to industrial weighing applications — MPE on initial verification is ±0.5e for loads up to 500e, ±1.0e for loads between 500e and 2000e, and ±1.5e for loads between 2000e and 10000e, with in-service inspection limits set at twice these values [4]. This load-dependent structure means that the absolute permissible error grows with increasing platform load, and the relative permissible error becomes disproportionately large when the measured quantity represents a small fraction of the weigher's capacity.

This characteristic has direct implications for ingredient dosing applications. OIML R 76-1 establishes a minimum capacity of 20e for Class III instruments — the load below which weighing results may be subject to excessive relative error [4]. However, as noted by Mettler Toledo, MPE defined in legal metrology frameworks represents a threshold for instrument approval, not a direct measure of measurement uncertainty in process applications [9]. The practical implication is that an instrument operating within its verified MPE limits may still deliver dosing results whose associated uncertainty exceeds the process tolerance required by the formula — a condition that becomes particularly significant when the dosed quantity is small relative to the weigher's capacity or, as examined in this study, when the measurement is taken against a large accumulated platform load.

OIML R 61-1 governs automatic gravimetric filling instruments and defines the maximum permissible deviation (MPD) of each fill as the maximum permissible deviation from the average value of all fills in a test sequence [5]. R 61-1 further defines a rated minimum fill as the value of fill mass below which weighing results may be subject to errors exceeding permissible limits — establishing a formal metrological basis for minimum load requirements in automatic filling applications [5]. For cumulative weighers, R 61-1 additionally establishes that the MPE per individual load during influence factor tests is reduced by the square root of the minimum number of loads per fill, acknowledging that error compounds across successive weighing cycles [5]. The implications of this compounding behavior for bulk GIW batching systems are examined in Section 4.2.

2.2. Bulk Gain-In-Weight Batching 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 [3].

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 [3]. 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 [8]. This principle is particularly significant in batch manufacturing contexts where ingredient quantities must fall within specified formula tolerances.

2.3. Measurement Uncertainty in Industrial Manufacturing Systems

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 [8].

A complete measurement result requires three components — the best estimate of the measured value, the unit, and the associated measurement uncertainty [8]. 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.

GUM explicitly states that no calibration is complete without the determination of estimated measurement uncertainty [6]. 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 [5]. 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 [7]. 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 [7].

2.4 Batch Reporting Requirements in Industrial Practice

Batch production records in manufacturing industries are governed by a combination of regulatory requirements and industry guidance. These frameworks define the minimum content that a compliant batch report must contain, establishing the operational standard against which industrial reporting systems are evaluated.

In the pharmaceutical and food manufacturing sectors, FDA 21 CFR 211.188 specifies that batch production and control records shall include complete information relating to the production and control of each batch, including weights and measures of components used in the course of processing [1]. This regulation establishes the legal minimum for batch record content in FDA-regulated manufacturing environments and is widely referenced as a benchmark for good manufacturing practice across industries.

In the animal feed manufacturing sector, the Kansas State University Feed Manufacturing Guide specifies that each batch report should include time and date, formula name and number, ingredient names, ingredient lot numbers where applicable, ingredient quantities, theoretical and actual weight of ingredients added, storage location, and operator identification [2]. The guide further specifies that deviations from specification should not exceed 1% for ingredients with greater than 5 lb inclusion and 2% for ingredients less than 5 lb — establishing the tolerance thresholds against which dosing compliance is evaluated in feed manufacturing practice.

Neither framework includes measurement uncertainty as a required element of the batch production record. The absence of uncertainty representation in industrial batch reports therefore reflects the current state of established reporting standards rather than a deviation from them. This distinction is significant: it indicates that the metrological gap identified in this study is not an implementation oversight within any specific manufacturing system, but a structural absence at the level of the standards and regulations that govern batch reporting across industries.

3. 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 recognized the increasing digital integration of measurement systems within manufacturing environments and the importance of uncertainty information for reliable interpretation of measurement results [8]. 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 [8]. 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 [8].

Despite these developments, limited attention has been given to the implementation of measurement uncertainty within bulk GIW batching systems operating under SCADA-based manufacturing architectures. Existing literature provides methods for evaluating uncertainty at the instrument level [6, 7], 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 bulk GIW batching systems [1, 2].

The architecture of bulk GIW batching systems introduces an additional challenge absent from isolated weighing applications: the uncertainty associated with each dosing event depends not only on the requested ingredient quantity, but also on its position within the dosing sequence. As accumulated platform load increases with each successive ingredient, the uncertainty associated with later dosing events grows accordingly. Current practice addresses this by applying the highest uncertainty estimate — derived from weigher capacity — uniformly across all ingredients, preserving reliability at the cost of operational flexibility. A model that evaluates uncertainty dynamically based on actual sequence position would enable both goals to be pursued simultaneously.

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 [1, 2]. Consequently, uncertainty cannot be propagated through the cumulative dosing process nor reconstructed from historical production records, creating a disconnect between reported values and the metrological capability of the underlying measurement system.

This study addresses that gap by proposing a GUM-consistent conceptual framework for bulk GIW batching systems, integrating uncertainty evaluation at individual dosing events, uncertainty propagation through the cumulative batching sequence, and incorporation of uncertainty information into SCADA data records and manufacturing reports. Beyond metrological completeness, the framework provides a basis for dynamic feasibility assessment — enabling the system to evaluate ingredient compatibility against weigher capability at the sequence level, improving operational flexibility without compromising reliability.

4. Methodology

4.1. Field Observation and Practitioner Inquiry

Problem identification in this study was based on three complementary evidence sources: structured practitioner inquiry across multiple facilities, structural analysis of the SCADA dosing database, and review of applicable regulatory and industry reporting standards.

Structured informal inquiries conducted with colleagues across multiple operational roles — including production, quality control, PPIC, automation, and plant management personnel — across several animal feed manufacturing facilities revealed that key dosing parameters, including calibration accuracy standards and minimum dosing limits, are applied consistently in practice but without formal metrological grounding. No respondent was able to identify a documented source for these parameters, and neither could articulate a formal metrological argument either supporting or opposing them. This suggests that the operational gap identified in this study is recognized in practice, even where it cannot be formally expressed.

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. No uncertainty-related fields were identified, confirming that the system was not designed to capture, store, or propagate measurement uncertainty information.

Review of applicable regulatory and industry reporting standards — including FDA 21 CFR 211.188 [1] and the KSU Feed Manufacturing Guide [2] — established the minimum required content of batch production records in the investigated manufacturing context. Neither framework includes measurement uncertainty as a required element, confirming that the absence of uncertainty information in the investigated system reflects the current state of applicable standards rather than a deviation from them.

4.2. Metrological Analysis and Framework Derivation

Following problem identification, a metrological analysis was conducted to establish the formal relationship between weigher accuracy standards and the dosing tolerance requirements applicable in feed manufacturing batch production.

Measurement uncertainty in weighing instruments is not a fixed percentage of capacity but varies with applied load. OIML R 61-1 governs automatic gravimetric filling instruments and is definitionally the closer standard for GIW batching systems.

R 61-1 recognizes cumulative weighing as a distinct metrological category, defining a cumulative weigher as an automatic gravimetric filling instrument that effects the fill by more than one weighing cycle [5]. For cumulative weighers, R 61-1 establishes that the MPE per individual load during influence factor tests is reduced by the square root of the minimum number of loads per fill — acknowledging that error compounds across successive weighing cycles [5]. However, R 61-1's cumulative weigher framework assumes repeated dosing cycles of the same material in approximately equal load increments until a predetermined total fill is reached.

Bulk GIW batching differs fundamentally: multiple different ingredients, each with a different requested amount, are dosed sequentially onto an accumulating platform load. Each dosing event is metrologically unique — different ingredient, different requested amount, different accumulated platform load at the time of measurement. The $\sqrt{n}$ error reduction applicable to identical repeated cycles has no direct equivalent in a sequence of fundamentally different measurement events. Furthermore, R 61-1's verification framework requires repeated fills of identical preset values evaluated against their statistical average — a procedure that is operationally inapplicable to bulk GIW batching where preset values vary by ingredient and fill masses are large and non-repeating.

In practice, OIML R 76-1, which governs non-automatic weighing instruments, provides the most workable basis for evaluating weigher accuracy at a given platform load through its load-dependent MPE structure. This is consistent with observed industrial practice, where Class III R 76-1 parameters are applied as the metrological reference for dosing weighers in feed manufacturing facilities [4]. Importantly, R 61-1 addresses cumulative error at the instrument verification level but provides no mechanism for its evaluation during actual production operation — the gap this paper addresses.

For a representative hypothetical scenario used at Section 5, a Class III weigher with verification scale interval e = 0.5 kg and maximum capacity of 1500 kg is considered. The number of verification scale intervals n = Max/e = 3000, which falls within the Class III range of 500 to 10,000, confirming class applicability. The minimum capacity is 20e = 10 kg.

OIML R 76-1 establishes for Class III instruments that MPE is expressed as multiples of e across defined load thresholds. For in-service inspection, these are ±1.0e for loads up to 500e, ±2.0e for loads between 500e and 2000e, and ±3.0e for loads between 2000e and 10000e [4]. For the representative weigher with e = 0.5 kg, these thresholds correspond to platform loads of 0–250 kg, 250–1000 kg, and 1000–1500 kg, with absolute in-service MPE values of ±0.5 kg, ±1.0 kg, and ±1.5 kg across these ranges respectively.

The Kansas State University Feed Manufacturing Guide establishes the process-side tolerance against which weigher performance must be evaluated, specifying that deviations from specification should not exceed 1% for ingredients with inclusion greater than 5 lb, and 2% for ingredients less than 5 lb [2]. These tolerance bands represent the maximum allowable deviation between the formula requested amount and the actual delivered amount — the process standard against which metrological adequacy is assessed.

For an ingredient of requested amount W, the KSU allowed deviation is 0.01 × W for ingredients above the 5 lb threshold. In isolated weighing, the platform load equals the ingredient weight, so the applicable MPE tier is determined by the ingredient quantity itself. For a 100 kg ingredient weighed in isolation, the platform load is 100 kg = 200e, falling within the 0–500e range. The in-service MPE is therefore ±1.0e = ±0.5 kg. The KSU allowed deviation for a 100 kg ingredient is ±1% × 100 kg = ±1.0 kg. Since MPE ±0.5 kg is well within the KSU tolerance of ±1.0 kg, the weigher appears metrologically adequate for this ingredient in isolated weighing — standard compliance is satisfied and the dosing result would be reported as acceptable.

Setting in-service MPE equal to KSU allowed deviation establishes the minimum requested amount below which the weigher can no longer reliably meet formula tolerance at each load tier. For the representative weigher, this derivation yields minimum requested amounts of 50 kg at the 0–250 kg platform load tier, 100 kg at the 250–1000 kg tier, and 150 kg at the 1000–1500 kg tier. In isolated weighing, where platform load equals ingredient weight, a 100 kg ingredient sits comfortably within the first tier and satisfies its derived minimum of 50 kg with adequate margin.

The implications of this load-dependent minimum for bulk GIW batching — where platform load is not the ingredient weight alone but the accumulated gross weight of all previously dosed ingredients — are examined in Section 5.

4.3. Conceptual Framework Development

Building on the metrological derivation presented in Section 4.2, a GUM-consistent conceptual framework is proposed for Bulk GIW Batching systems [7, 8]. 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.

To evaluate the practical significance of the identified uncertainty gap, a representative hypothetical scenario is constructed in Section 5. The scenario models a feed formula processed through Class III weigher defined under OIML R76, and the resulting expanded uncertainties are benchmarked against the dosing tolerance bands specified in the KSU Feed Manufacturing Guide.

This paper presents the framework at a conceptual level and focuses on establishing the metrological need for uncertainty integration within SCADA-based Bulk GIW Batching 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.

5. Results and Discussion

Throughout this section, a hypothetical setup is used to illustrate how measurement uncertainty affects product conformity to formula and how it is represented — or absent — in batch production records. The setup is based on a real production formula from an operating feed manufacturing facility, with ingredient names anonymized and requested amounts slightly modified. The weigher specification and allowed deviation follow internationally recognized standards applicable to industrial feed manufacturing practice.

The formula is presented in Table 1.

Ingredient	Request (kg)
Material A	122
Material B	872
Material C	118
Material D	118
Material E	132

Table 1. Sample Formula.

The weigher is specified as a Class III automatic bulk GIW weigher with maximum capacity 1500 kg and verification scale interval e = 0.5 kg, in accordance with OIML R 76-1 [4]. The number of verification scale intervals n = Max/e = 3000, confirming Class III applicability. The total batch weight of 1363 kg falls within the weigher's maximum capacity.

The allowed deviation follows the Kansas State University Feed Manufacturing Guide, which specifies that deviations from specification should not exceed 1% of the requested amount for ingredients with inclusion greater than 5 lb [2]. All five ingredients in the formula exceed this threshold. The allowed deviation is therefore ±1% of the requested amount for each ingredient, applied uniformly across the formula.

5.1. From Load Cells to Database.

Before discussing the main topic of measurement uncertainty in Bulk GIW Batching 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 [5].

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.

5.2. The Uncertainty in Concrete Number

The following report represents a hypothetical dosing record constructed to illustrate the type of information typically generated by computerized batch production systems in feed manufacturing facilities. The format, structure, and reported parameters reflect actual industrial practice, and the scenario is consistent with the hypothetical weigher specification and formula presented in this study. Material names have been anonymized.

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

It is also important to note that the dosing report examined in this study conforms to established batch reporting requirements, including those specified in FDA 21 CFR 211.188 [1] and industry guidance such as the KSU Feed Manufacturing Guide [2]. The absence of measurement uncertainty information therefore reflects not a deviation from standard practice, but the current state of the standard itself.

Ingredient	Request (kg)	Delivered (kg)	Dev (kg)	TOL (kg)	TL
Material A	122	121.5	-0.5	1.22	0
Material B	872	872	0	8.72	0
Material C	118	119	1	1.18	0
Material D	118	117.5	-0.5	1.18	0
Material E	132	132.5	0.5	1.32	0

Table 2. Sample of a detailed batch report.

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 = Dlv - Req).

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

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 Bulk GIW Batching systems this uncertainty could become bigger than the applied tolerance can accommodate.

5.3. 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 [5]. In the dosing system under investigation, macro ingredient weighers operate with a display resolution of 0.5 kg, meaning measurements are presented in discrete 0.5 kg increments.

As a consequence, every displayed measurement inherently contains uncertainty associated with the resolution limit itself [6]. 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 [6]:

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

For the dosing weighers under investigation, where $d = 0.5$ kg:

$u(res) = 0.5 / (\sqrt{3}) = 0.5 / 1.732 = 0.289$ kg

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

$U(res) = 2 \times 0.289 = \pm 0.577$ 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 1 kg within an allowed tolerance of ±1.18 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:

1 ± 0.577 kg = 0.423 kg to 1.577 kg

The upper bound of this range, 1.577 kg, already exceeds the allowed tolerance of ±1.18 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.

Material B is safe due to its large tolerance margin. Material A, D and E clears tolerance by a narrow margin that the second uncertainty source will challenge further.

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 Bulk GIW Batching systems — one that grows with each successive dosing event and cannot be recovered from existing production records.

5.4. 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 depend 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 [6]:

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

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:

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

$U(rep) = 2 \times 0.050 = \pm 0.100$ 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 [6]:

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

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

$= \sqrt{(0.084 + 0.0025)}$

$= \sqrt{0.086}$

$= 0.293$ 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.

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, now the upper bound is even further from the tolerated deviation, with reading and measurement uncertainty arrived at:

1 ± 0.587 kg = 0.413 kg to 1.587 kg

5.5. Third Source of Uncertainty: Accumulated Platform Load in Bulk GIW Batching System

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 is structurally inherent to Bulk GIW Batching systems and, as will be demonstrated, grows with each successive dosing event.

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. 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.

Before examining the GIW-specific condition, it is instructive to first evaluate each ingredient under the assumption of isolated weighing — that is, where each ingredient is weighed independently on an empty platform. This represents the condition assumed by OIML R 76-1 and reflects how dosing weigher performance is typically evaluated during calibration and verification.

Under isolated weighing conditions, the platform load at the time of measurement equals the ingredient weight itself. For the representative Class III weigher with e = 0.5 kg, the applicable R76 in-service MPE tier is determined by the ingredient quantity alone. Table 3 presents the isolated weighing evaluation for each ingredient.

Ingredient	Request (kg)	Delivered (kg)	Dev (kg)	TOL (kg)	TL	R76 MPE isolated (kg)	u(R76 MPE) (kg)	u (combined) kg
Material A	122	121.5	-0.5	1.22	0	0.5	0.289	0.412
Material B	872	872	0	8.72	0	1	0.577	0.648
Material C	118	119	1	1.18	0	0.5	0.289	0.412
Material D	118	117.5	-0.5	1.18	0	0.5	0.289	0.412
Material E	132	132.5	0.5	1.32	0	0.5	0.289	0.412

Table 3. Uncertainty evaluation under isolated weighing assumption.

Where U combined isolated is calculated as:

$u(\text{load}) = \text{MPE} / \sqrt{3}$

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

U combined = 2 × u(c)

For Materials A, C, D, and E in isolated weighing, platform load = ingredient weight, falling within the 0–500e range, giving R76 MPE = ±0.5 kg and $u(\text{load}) = 0.5/\sqrt{3} = 0.289$ kg:

$u(c) = \sqrt{0.289^2 + 0.050^2 + 0.289^2} = \sqrt{0.0835 + 0.0025 + 0.0835} = \sqrt{0.1695} = 0.412$ kg

U combined = ±0.824 kg

For Material B, platform load = 872 kg = 1744e, falling within the 500–2000e range, giving R76 MPE = ±1.0 kg and $u(\text{load}) = 1.0/\sqrt{3} = 0.577$ kg:

$$u(c) = \sqrt{(0.289^2 + 0.050^2 + 0.577^2)} = \sqrt{(0.0835 + 0.0025 + 0.3329)} = \sqrt{0.4189} = 0.647 \text{ kg}$$

U combined = ±1.294 kg

Under the isolated weighing assumption, all five ingredients show combined expanded uncertainty well within their respective KSU tolerance bands. The dosing report, the R76 calibration standard, and KSU tolerance bands all agree: the batch appears metrologically sound.

Ingredient	Request (kg)	Delivered (kg)	Dev (kg)	TOL (kg)	U(combined) kg
Material A	122	121.5	-0.5	1.22	0.824
Material B	872	872	0	8.72	1.294
Material C	118	119	1	1.18	0.824
Material D	118	117.5	-0.5	1.18	0.824
Material E	132	132.5	0.5	1.32	0.824

Table 4. Expanded Uncertainty under isolated weighing assumption.

This agreement, however, rests entirely on the isolated weighing assumption — the assumption that each ingredient is measured against an empty platform. In Bulk GIW Batching systems, this assumption does not hold.

5.6. The Misapplication in Bulk GIW Batching

In a Bulk GIW batching 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 Bulk GIW Batching 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	Request (kg)	Delivered (kg)	Acc. Delivered (kg)
Material A	122	121.5	121.5
Material B	872	872	993.5
Material C	118	119	1112.5
Material D	118	117.5	1230
Material E	132	132.5	1362.5

Table 5. Between the reported amount and the real measured amount by the digital weigher.

At the moment Material C is dosed, the platform carries an accumulated load of 993.5 kg from Materials A and B. The total platform load at the completion of Material C dosing is approximately 1,112.5 kg.

Applying the R76 MPE to the accumulated platform load at the time of Material C measurement fall to range of $2\,000.d < m \le 10\,000.d$ [4]:

$u(\text{load}) = 1.5/\sqrt{3} = 0.866$ kg

$U(\text{load}) = 2 \times 0.866 = \pm 1.732$ kg

This uncertainty component alone already exceeds the allowed tolerance for Material C (±1.18 kg), Material D (±1.18 kg), and Material E (±1.32 kg). Unlike the resolution and repeatability components derived previously, this uncertainty is not fixed — it is specific to the material's position in the dosing sequence and the accumulated load present at that moment.

5.6.1. 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 [6]:

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

$= \sqrt{0.289^2 + 0.050^2 + 0.866^2}$

$= \sqrt{0.0835 + 0.0025 + 0.75}$

$= \sqrt{0.836}$

= 0.914 kg

The expanded combined uncertainty at k = 2 is:

U(combined) = 2 × 0.914 = ±1.829 kg

Applying this to Material C's recorded deviation of 0.5 kg:

Actual deviation range = 1 ±1.829 kg = -2.329 kg to +1.329 kg

The dosing report records Material C as compliant — deviation 0.5 kg within tolerance ±1.18 kg, no alarm triggered. The combined uncertainty evaluation reveals that the actual delivered quantity may deviate from the requested amount by up to -2.329 kg, a range more than twice the allowed tolerance. This result is entirely invisible in the computerized dosing report.

It is also important to take into account the common practice within the industry, where process tolerance is always set lower than the tolerance of the formula itself. Thus, failing to comply with process tolerance doesn't immediately mean it fails to comply with the formula tolerance.

However, as we will later see, the actual uncertainty in a Bulk GIW Batching system would increasingly grow as it doses a later ingredient. A problem of uncertainty that uniquely existed in this particular dosing system.

5.6.2. 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)	Acc. Delivered (kg)	TOL (kg)	R76 MPE isolated (kg)	u (combined) kg	U (combined) kg
Material A	121.5	121.5	1.22	0.5	0.4115	0.823

Material B	872	993.5	8.72	1	0.6476	1.295
Material C	119	1112.5	1.18	1.5	0.9143	1.829
Material D	117.5	1230	1.18	1.5	0.9143	1.829
Material E	132.5	1362.5	1.32	1.5	0.9143	1.829

Table 6. Detailed batch report, with uncertainty factor calculated based on actual weigher reading.

At the moment Material D and E are dosed, the platform carries beyond 1000 kg and applying R76 Class III MPE, carry the same expanded uncertainty as Material C at ±1.829 kg. Bring Material D actual deviation range at -2.329 to 1.329 kg, and Material E actual deviation range at -1.329 to 2.329 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 Bulk GIW Batching 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 3.

5.6.3. Reference Chain Uncertainty in Bulk GIW Batching

Beyond the uncertainty associated with the accumulated platform load, Bulk GIW Batching 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 Bulk GIW Batching 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 [6]:

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

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 its respective load conditions at the time of capture.

Consequently, the combined uncertainty for ingredients dosed beyond the first position in the sequence is systematically larger than estimates based on the final platform reading alone.

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 993.5 kg immediately before dosing begins, and the final reading at 1,112.5 kg when dosing completes. Each reading carries its own load-proportional uncertainty. At 993.5 kg, $u(\text{ref}) = 0.648$ kg; at 1,113 kg, $u(\text{load}) = 0.914$ kg. The combined uncertainty of Material C's delivered weight is therefore:

$$u(\text{combined}) = \sqrt{0.648^2 + 0.914^2} = \sqrt{0.42 + 0.835} = \sqrt{1.255} = 1.12 \text{ kg}$$

$$U(\text{combined}) = 2 \times 1.12 = \pm 2.24 \text{ kg}$$

This is larger than the ±1.829 kg reported in the preceding section, which accounted only for the final reading uncertainty. The difference — 0.412 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)	Acc. Load (kg)	u(ref. combined) (kg)	u(acc. combined) (kg)	u(ref + acc) (kg)	U (±kg)	DEV (kg)	TOL (±kg)	Actual Dev. Range (kg)
Material A	121.5	121.5	0	0.4115	0.4115	0.823	-0.5	1.22	-1.323 to 0.323
Material B	872	993.5	0.4115	0.6476	0.767	1.534	0	8.72	-1.534 to 1.534
Material C	119	1,112.5	0.6476	0.9143	1.12	2.24	1	1.18	-1.24 to 3.24

Material D	117.5	1,230	0.9143	0.9143	1.293	2.586	-0.5	1.18	-3.086 to 2.086
Material E	132.5	1,362.5	0.9143	0.9143	1.293	2.586	0.5	1.32	-2.086 to 3.086

Table 7. Detailed batch report with uncertainty from reference weight and actual reading weight.

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 ±2.586 kg for Material D and E, against a tolerance of ±1.18 and ±1.32 kg.

It is important to note that the uncertainty associated with an ingredient measurement exceeds the expanded uncertainty specified for the weighing instrument at its maximum capacity, but calculated as a single isolated weighing, because in GIW batching system, the measurement uncertainty from second material onward, is not obtained from a single weighing result but from the subtraction of two independent measurements, each carrying its own uncertainty contribution.

Thus, the maximum measurement uncertainty in a Bulk GIW Batching System is larger than a normal weighing system.

Two straightforward approaches can solve measurement uncertainty in a Bulk GIW Batching System.

The first is to place small ingredients earlier in the dosing sequence, where platform loads are lower. The second is to conservatively assign all ingredients an uncertainty equal to the maximum uncertainty calculated at full weighing capacity.

Both approaches, however, introduce operational disadvantages. In industrial practice, large bulk ingredients are often dosed first because they help minimize material losses caused by mechanical gaps, leakage paths, or residual material retention within the system. Likewise, assigning the maximum uncertainty to every ingredient may unnecessarily restrict production flexibility and increase the likelihood of rejecting otherwise acceptable formulations.

A more practical solution is therefore desirable. This paper proposes a dynamic uncertainty model in which the expected measurement uncertainty of each ingredient is calculated in advance from the formulation sequence and weighing instrument characteristics. The resulting uncertainty values can be incorporated into formulation design, production verification, and manufacturing reporting before the recipe is released for production.

5.7. Implications of Missing Measurement Uncertainty Model in Planning and Evaluating Production Process.

The absence of embedded uncertainty information has implications at two distinct levels of manufacturing reporting. At the batch level, it affects ingredient compliance assessment and formula conformity decisions. At the aggregated level, it undermines inventory reconciliation, material consumption reporting, and production performance evaluation.

Each is examined in turn.

5.7.1. Less Flexibility in Planning the Production Process

As already mentioned in Section 4.1. Minimum dosing parameters often become a debate between the QC division and the production division. It sits between several principles that become the foundation of Industrie 4.0: Fast, Accurate, Reliable, Flexible, and Holistic [8].

A strict minimum dosing parameter that is defined by the highest measurement uncertainty of the weigher is reliable, but often time cause problem in operational production planning. Existing weighers in the factory might not be available for certain ingredients in the formula, leading to manual preparation of that ingredient. This is the dynamic trade-off between speed, reliability, and flexibility.

As we can see from Section 5.6.3, without assigning an ingredient to another weigher, it is possible to achieve measurement uncertainty below the allowed tolerance by changing the sequence of an ingredient within the formula. At the same time, by knowing the potential measurement uncertainty of each sequence, it is now possible to calculate the highest process tolerance that still conforms to the formula tolerance.

As such, the implementation of measurement uncertainty within the Bulk GIW Batching SCADA system increases reliability while maintaining flexibility.

5.7.2. Unreliable Detailed Process Report

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 [6][7].

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.

5.7.3. 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 Bulk GIW Batching system 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. 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 the Bulk GIW Batching system means that a single uniform error margin applied across all materials becomes metrologically misleading [6].

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 [8].

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 [8]. 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 [1][6].

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 [6][7].

5.8. Proposed Solution

The analysis presented in this study demonstrates that the absence of an embedded measurement uncertainty model within the investigated SCADA architecture creates three fundamental limitations arising directly from the operating principles of the Bulk GIW Batching system. Although the system continuously records weight values throughout the manufacturing process, it provides no mechanism to evaluate, store, propagate, or report the uncertainty associated with those measurements. As a result, uncertainty information is effectively discarded at the point of measurement and cannot be reconstructed from historical production records.

To address this limitation, this paper proposes a conceptual framework in which measurement uncertainty is treated as an operational process parameter rather than solely as a calibration attribute existing outside the manufacturing information system. Under this approach, uncertainty information accompanies measurement data throughout the production lifecycle and becomes available for manufacturing records, quality verification, process analysis, and regulatory documentation. The framework employs a hybrid uncertainty evaluation methodology that combines multiple uncertainty contributors relevant to industrial dosing systems.

5.8.1. Uncertainty Model

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 [7].

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 [7].

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 [8].

Third, uncertainty associated with load-dependent instrument behavior is evaluated through periodic calibration and verification activities conducted at multiple points throughout the weighing range [4, 5]. The combined expanded uncertainty at each dosing event is evaluated using the GUM law of propagation of uncertainty [6]:

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

$U(\text{combined}) = k \times u(\text{combined})$, where $k = 2$ for approximately 95% confidence

Because each ingredient's delivered weight is determined as the difference between two successive platform readings, the complete uncertainty evaluation must account for both the reference reading taken before dosing begins and the final reading taken after dosing completes [6]:

$$u(\text{delivered}) = \sqrt{u(\text{ref combined})^2 + u(\text{acc combined})^2}$$

This formulation, demonstrated in Table 7, produces systematically larger uncertainty estimates than those based on the final platform reading alone — and represents the metrologically correct treatment for derived quantities in sequential measurement systems.

5.8.2. Pre-Dosing Feasibility Assessment

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 the Bulk GIW Batching 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.

To illustrate, consider a formula with tolerance following Kansas State University’s good feedmill manufacturing practice, is assigned to a class III weigher with 0.5 kg resolution and 1,500 kg capacity:

Ingredient	Request (kg)	Accumulated Load (kg)	TOL (kg)
Material A	120	120	1.2
Material B	875	995	8.75
Material C	120	1,115	1.2
Material D	115	1,230	1.15
Material E	130	1,360	1.3

Table 8. Sample Random Formula

Without measurement uncertainty in the SCADA, we put it against the highest possible measurement uncertainty.

$u(\text{combined}) = \surd(0.289^2 + 0.050^2 + 0.866^2 = \surd 0.836 = 0.914$

$u(\text{ref + load combined}) = \surd(0.914^2+0.914^2) = \surd 1.671 = 1.293$

$U(\text{combined}) = 2.586$

Ingredient	Request (kg)	Accumulated Load (kg)	TOL (kg)	U(at cap.)
Material A	120	120	1.2	2.586
Material B	875	995	8.75	2.586
Material C	120	1,115	1.2	2.586
Material D	115	1,230	1.15	2.586
Material E	130	1,360	1.3	2.586

Table 9. Sample Random Formula, Evaluate Against Max possible Measurement Uncertainty

Under this uniform assessment, only Material B, with a formula tolerance of ±8.75 kg, can be confirmed compatible with this weigher. All remaining ingredients fall outside metrological acceptability.

When the SCADA applies the uncertainty model dynamically — evaluating uncertainty at the actual accumulated load for each sequence position — the assessment changes substantially:

Ingredient	Delivered (kg)	Accumulated Load (kg)	u(total) (kg)	u(combined) (kg)	U	TOL (kg)
Material A	120	120	0.4115	0.4115	0.823	1.2
Material B	875	995	0.6476	0.767	1.534	8.75
Material C	120	1,115	0.9143	1.12	2.24	1.2
Material D	115	1,230	0.9143	1.293	2.586	1.15
Material E	130	1,360	0.9143	1.293	2.586	1.3

Table 10. Sample Random Formula, Evaluate Against Measurement Uncertainty per Step

Materials A and B are now confirmed compatible. Materials C, D, and E remain outside tolerance — but the model reveals that this is a consequence of their sequence position, not their quantity alone. By reordering the sequence to place lighter ingredients first, the accumulated platform load at each event is reduced, and the uncertainty associated with every ingredient decreases accordingly:

Ingredient	Delivered (kg)	Accumulated Load (kg)	u(total) (kg)	u (combined) (kg)	U	TOL (kg)
Material D	115	115	0.4115	0.4115	0.823	1.15
Material A	120	235	0.4115	0.582	1.164	1.2
Material C	120	355	0.4115	0.582	1.164	1.2
Material E	130	485	0.4115	0.582	1.164	1.3
Material B	875	1,360	0.9143	1.003	2.006	8.75

Table 11. Sample Random Formula, Evaluate After New Sequence Arrangement

Sequence reordering alone — without any hardware change or weigher reassignment — brings all five ingredients within their respective formula tolerances. This demonstrates a degree of operational flexibility that is entirely invisible to a SCADA implementation without an embedded uncertainty model.

The SCADA can further assist production planning by calculating a suggested process tolerance for each ingredient: the formula tolerance reduced by the ceiling of the expanded uncertainty, ensuring the process tolerance remains above the metrological noise floor while still conforming to the formula requirement.

Ingredient	Delivered (kg)	Accumulated Load (kg)	u(total) (kg)	u(combined) (kg)	U	TOL (kg)	Suggested TOL (kg)
Material D	115	115	0.4115	0.4115	0.823	1.15	0.327
Material A	120	235	0.4115	0.582	1.164	1.2	0.036
Material C	120	355	0.4115	0.582	1.164	1.2	0.036
Material E	130	485	0.4115	0.582	1.164	1.3	0.136
Material B	875	1,360	0.9143	1.003	2.006	8.75	6.744

Table 12. Sample Random Formula, with Suggested Process Tolerance

5.8.3. Uncertainty-Aware Process Execution and Reporting

During dosing execution, the SCADA can evaluate and record expanded uncertainty at each dosing event as it occurs, propagating it through the cumulative sequence in real time. If at any point the recalculated uncertainty for the next ingredient exceeds its formula tolerance — due to accumulated platform load exceeding anticipated conditions — the system can issue an early warning before the event is committed, giving the operator the option to transfer the ingredient to an alternative weigher or prepare it manually.

By recording uncertainty alongside each delivered weight value, the SCADA preserves the metrological basis of every dosing event within the batch history. This information can then be carried through to aggregated manufacturing reports, where material consumption figures are presented with their associated uncertainty rather than as deterministic quantities — consistent with the requirement that a complete measurement result includes the best estimate of the measured value, its unit, and its associated uncertainty [6][8].

Such integration transforms measurement uncertainty from a calibration-related concept into an operational parameter present throughout production planning, dosing execution, and manufacturing report interpretation.

6. Conclusion

Measurement uncertainty is a fundamental component of a complete measurement result [6][8]. However, uncertainty information is generally absent from SCADA-based Bulk GIW Batching 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 the Bulk GIW Batching 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 sequential cumulative dosing systems. While production reports record nominal ingredient weights, the associated uncertainty information is discarded and cannot be reconstructed from historical manufacturing records.

Furthermore, analysis of the Bulk GIW batching process showed that ingredient measurements are obtained from the difference between two weighing results, each contributing its own measurement uncertainty. As a consequence, the uncertainty associated with an ingredient may exceed the expanded uncertainty specified for a single weighing result at maximum scale capacity. This finding demonstrates that the common industrial practice of applying a single worst-case scale uncertainty is insufficient to fully characterize uncertainty within sequential cumulative dosing operations.

To address the identified gap, a GUM-consistent conceptual framework [6, 7] 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[8].

The principal contribution of this work is the identification of uncertainty propagation as an inherent metrological challenge in the Bulk GIW Batching 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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Declaration use of generative AI

During the preparation of this work, the author(s) used Claude and ChatGPT for beta read, editing and grammar check. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

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