End-to-End Instance-Level Torque Management Across the Automotive Manufacturing Lifecycle

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Abstract

Torque accuracy is critical to ensuring safety, reliability, and structural integrity in automotive assemblies, particularly for high-reliability systems such as engines, chassis, and suspension components. Traditional part-based torque definitions are insufficient for modern vehicle architectures where identical fasteners are reused across multiple locations with differing functional and reliability requirements. This paper presents an instance-based torque definition model implemented within a Product Lifecycle Management (PLM) environment, enabling precise torque specification, traceability, and execution across the engineering and manufacturing lifecycle. Using the 3DEXPERIENCE platform and DELMIA digital manufacturing solutions, the proposed approach demonstrates how torque data authored at the Engineering Bill of Materials (EBOM) instance level can be propagated through Manufacturing BOM (MBOM), Bill of Process (BOP), and Manufacturing Execution Systems (MES). The model enhances process control, improves auditability, and supports high-reliability automotive manufacturing.

Keywords: Product lifecycle management; Torque management; 3DEXPERIENCE; DELMIA; EBOM; MBOM; BOP; MES; automotive manufacturing; digital continuity; fastener management.

1. Introduction

Torque-controlled fastening is a fundamental aspect of automotive manufacturing, directly influencing vehicle safety, performance, and long-term reliability. Modern automobiles are composed of thousands of mechanical joints, many of which are part of high-reliability systems such as engines, powertrain assemblies, braking systems, suspension, and structural chassis components. In these systems, improper torque application can result in insufficient clamping force, joint loosening, fatigue failure, or even catastrophic component separation. Consequently, precise torque management is a critical requirement throughout the product lifecycle, from design and engineering to manufacturing execution and quality assurance.

In contemporary vehicle architecture, fasteners are rarely unique to a single application. A single bolt or screw design may be reused across numerous assemblies and subassemblies, often under very different functional and environmental conditions. Although the fastener reference remains identical, each instance may experience varying loads, thermal cycles, vibration profiles, material pairings, and safety requirements. Additionally, factors such as surface finish, thread condition, lubrication, tightening sequence, and tool accuracy introduce significant variability in the relationship between applied torque and resulting joint preload. These variations make it increasingly difficult to ensure consistent and reliable joint performance using traditional torque definition methods.

Conventional torque management practices in automotive Product Lifecycle Management (PLM) systems typically associate torque specifications with the fastener part reference. While this approach simplifies data management, it fails to capture the contextual differences between individual fastener usages. As a result, part-based torque definitions often lead to over-tightening or under-tightening in certain locations, increased rework on the shop floor, and reduced confidence in residual torque verification. Furthermore, manual work instructions and disconnected documentation limit traceability and make compliance audits and root-cause analysis both time-consuming and error-prone.

As automotive products become more complex and regulatory requirements continue to tighten, manufacturers are increasingly dependent on digital continuity between engineering intent and manufacturing execution. High-reliability assemblies, particularly those using torque-to-yield fasteners, require not only precise torque strategies but also full traceability of torque application, verification results, and process deviations. The absence of an integrated, instance-level torque definition model creates gaps in this digital thread, undermining quality control and increasing operational risk.

To overcome these limitations, this paper introduces an instance-based torque definition model that assigns torque specifications to individual fastener instances rather than to part references. In this model, each fastener instance is uniquely identified within the assembly structure and enriched with torque-related attributes such as tightening strategy, torque and angle tolerances, joint criticality, and residual torque limits. This approach enables torque requirements to be tailored precisely to the functional role of each joint, supporting both engineering accuracy and manufacturing consistency.

The proposed instance-based model is implemented within the 3DEXPERIENCE PLM platform, integrated with DELMIA digital manufacturing solutions. Torque data authored in the Engineering Bill of Materials (EBOM) is systematically propagated to the Manufacturing Bill of Materials (MBOM), Bill of Process (BOP), and Manufacturing Execution Systems (MES) through established traceability mechanisms. This end-to-end digital workflow ensures that torque specifications defined by engineering are accurately executed on the shop floor, captured during assembly, and made available for quality analysis and compliance verification.

By establishing a closed-loop, instance-level torque management framework, the approach presented in this paper enhances torque consistency, improves audit readiness, reduces manufacturing rework, and strengthens overall product reliability. The remainder of this paper details the torque strategies involved, the underlying data model, implementation considerations, and the benefits of instance-based torque definition for high-reliability automotive assemblies.

2. Related Work

Torque management and fastening control have been extensively studied in the context of automotive manufacturing due to their direct impact on safety, reliability, and product quality. Prior research primarily focuses on tightening strategies, torque–preload relationships, digital manufacturing systems, and PLM-driven traceability. However, limited work addresses torque definition at the fastener instance level across the full product lifecycle.

2.1 Torque–Preload Relationship and Tightening Strategies

Several studies have examined the relationship between applied torque and resulting joint preload, highlighting the dominant influence of friction at the threads and under the fastener head. Research has shown that only 10–15% of applied torque contributes to useful clamping force, while the remainder is lost to friction, resulting in significant preload variability even under controlled conditions [1], [2].

To mitigate this variability, torque-plus-angle tightening methods have been widely adopted in automotive powertrain and chassis assemblies. This approach improves preload consistency by stretching torque-to-yield fasteners beyond their elastic limit, reducing sensitivity to friction variations [3]. Standards and guidelines from organizations such as SAE and ISO formalize the use of angle-controlled tightening for safety-critical joints [4].

While these studies establish best practices for tightening strategies, they primarily address process-level control rather than data modeling and lifecycle traceability of torque specifications.

2.2 Residual Torque Measurement and Quality Assurance

Residual torque measurement has long been recognized as an effective indicator of joint integrity and preload retention. Breakaway and loosen–tighten methods are commonly referenced in both academic literature and industry standards for post-assembly verification [5].

Recent studies emphasize the importance of residual torque data in detecting joint relaxation caused by thermal cycling, vibration, and material creep, particularly in engine and powertrain applications [6]. However, residual torque data is often collected in isolation within manufacturing systems and lacks a direct digital link to engineering-defined torque intent, limiting its effectiveness for closed-loop quality control.

2.3 Digital Manufacturing and Torque Control Systems

The adoption of Manufacturing Execution Systems (MES) and digitally controlled tightening tools has significantly improved torque application accuracy and data capture on the shop floor. Modern MES platforms integrate torque tools to enforce parameter validation, capture tightening results, and support traceability for regulatory compliance [7].

Despite these advancements, torque specifications are frequently transferred to MES as static values derived from part-based documentation. This limits flexibility and creates challenges when identical fasteners require different torque strategies depending on their functional context.

2.4 PLM-Based Traceability and Product Structure Modeling

Product Lifecycle Management (PLM) systems provide the digital backbone for managing product definitions, configurations, and manufacturing data. Prior research highlights the importance of maintaining traceability between Engineering Bill of Materials (EBOM), Manufacturing Bill of Materials (MBOM), and Bill of Process (BOP) to ensure consistency between engineering intent and manufacturing execution [8], [9].

Several studies discuss instance-level modeling within PLM for managing configuration-specific attributes such as position, orientation, and effectivity [10]. However, torque attributes are typically treated as document-based or reference-level parameters, rather than being modeled as instance-specific characteristics associated with individual fastener usages.

2.5 Research Gap

Although existing literature addresses torque strategies, residual torque verification, digital manufacturing systems, and PLM traceability independently, there is a notable gap in research that integrates these domains through an instance-based torque definition model. Current approaches lack a unified framework that allows torque specifications to be authored at the fastener instance level and propagated seamlessly across EBOM, MBOM, BOP, and MES systems.

This gap motivates the instance-based torque definition model presented in this paper, which aims to establish end-to-end digital continuity, improve torque accuracy, and support high-reliability automotive assemblies.

3. Torque Management in Automotive Manufacturing

Torque management is a core element of automotive manufacturing that ensures mechanical joints meet safety, durability, and functional performance requirements. Modern vehicles contain thousands of fasteners distributed across a wide range of assemblies, from non-critical auxiliary components to high-reliability systems such as engines, powertrain, suspension, braking, and structural chassis modules. In these applications, improper torque application can lead to joint loosening, fatigue failure, component deformation, or loss of structural integrity. Consequently, torque control is not only a manufacturing concern but a critical aspect of overall product reliability and compliance.

3.1 Torque Fundamentals and Joint Behavior

Torque is applied to threaded fasteners as an indirect means of generating clamping force, commonly referred to as joint preload. While torque is easy to measure and control, the relationship between applied torque and resulting preload is highly non-linear and strongly influenced by friction. A significant portion of the applied torque is dissipated through friction at the threads and under the fastener head, with only a small fraction contributing to useful clamping force. As a result, identical torque values can produce widely varying preload levels depending on surface condition, lubrication, material properties, and fastener geometry.

In automotive assemblies, joint behavior is further affected by component stiffness, thermal expansion, vibration, and tightening sequence. These factors are particularly critical in high-reliability assemblies, where even small variations in preload can compromise joint integrity over the vehicle's operational life. Understanding these joint mechanics is essential for selecting appropriate torque strategies and defining acceptable tolerance limits.

3.2 Torque Strategies in Automotive Assemblies

To manage preload variability and achieve consistent joint performance, automotive manufacturers employ standardized torque strategies based on joint function and criticality. The most commonly used approach is the target torque strategy, in which a nominal torque value and tolerance range are specified. This strategy is suitable for joints where moderate preload variation does not significantly affect system performance and is widely used in non-critical and semi-critical applications.

For safety-critical and high-reliability joints, manufacturers often adopt the torque-plus-angle strategy, particularly when using torque-to-yield fasteners. In this approach, the fastener is first tightened to a predefined torque to seat the joint, followed by a controlled angular rotation that stretches the fastener. This controlled elongation produces a more consistent preload that is less sensitive to frictional variation, making it well-suited for engine, powertrain, and suspension assemblies. By aligning the tightening process with material behavior, this strategy improves joint reliability and repeatability.

3.3 Quality Verification and Digital Torque Control

Quality verification is an essential component of torque management in automotive manufacturing. Residual torque measurement is commonly used to assess the retained preload in a joint after assembly and thermal cycling. Techniques such as breakaway torque measurement and loosen–tighten verification provide valuable insight into joint stability and tightening effectiveness, particularly for high-reliability applications.

With the increasing adoption of digital manufacturing systems, torque management has evolved beyond manual tools and paper-based instructions. Modern production lines integrate digitally controlled tightening tools with Manufacturing Execution Systems (MES) to enforce torque parameters, capture tightening results, and provide real-time feedback to operators. This digital integration enhances process control, improves traceability, and supports compliance with quality and regulatory requirements.

Despite these advancements, torque data used in manufacturing execution is often derived from static, part-based definitions that do not fully reflect the functional context of individual fastener applications. This limitation creates challenges when identical fasteners require different torque strategies depending on their usage, highlighting the need for a more granular and context-aware torque definition approach.

4. Limitations of Part-Based Torque Definition Models

Despite significant advancements in fastening tools, digital manufacturing systems, and quality assurance practices, torque management in many automotive organizations continues to rely on part-based torque definition models. In this approach, torque specifications are associated with the fastener reference rather than with individual fastener usages within an assembly. While this methodology simplifies data administration, it introduces fundamental limitations that become increasingly problematic in high-reliability automotive assemblies where precision, traceability, and contextual accuracy are critical.

4.1 Absence of Context-Specific Torque Definition

Part-based torque models assume that a single torque specification is sufficient for all applications of a given fastener. However, in real-world automotive assemblies, identical fasteners are frequently used in joints with significantly different functional roles, loading conditions, and safety requirements. A fastener used in a non-critical bracket, for example, may tolerate a wide preload variation, whereas the same fastener used in a powertrain or suspension joint may require highly controlled tightening to ensure structural integrity.

Because part-based models lack the ability to capture the functional context of individual fastener instances, torque values are often defined conservatively or supplemented with external documentation. This disconnect increases the risk of incorrect torque application on the shop floor and undermines the ability to consistently meet engineering intent across all fastener usages.

4.2 Limited Traceability and Quality Visibility

High-reliability automotive manufacturing demands full traceability of torque application, particularly for safety-critical joints subject to regulatory and customer audits. Part-based torque definitions provide limited visibility into which torque values and tightening strategies were applied to specific fastener instances during assembly. As a result, quality data collected during manufacturing cannot be easily correlated with engineering-defined torque intent.

This lack of instance-level traceability complicates root-cause analysis when quality issues arise. Manufacturers may be unable to determine whether a failure is linked to a specific joint location, tightening sequence, or assembly condition. In complex assemblies with hundreds of identical fasteners, the inability to distinguish between individual instances significantly reduces the effectiveness of quality containment and corrective actions.

4.3 Inefficient Change Management and Digital Continuity

Automotive products undergo frequent engineering and process changes throughout their lifecycle, driven by design optimization, regulatory requirements, and continuous improvement initiatives. In part-based torque models, modifying a torque specification at the fastener reference level affects all instances of that fastener across the product structure, regardless of whether the change is applicable to every usage.

To mitigate this risk, organizations often resort to workarounds such as creating duplicate fastener part numbers, adding manual overrides in manufacturing systems, or maintaining separate documentation for specific applications. These practices increase data complexity, introduce inconsistencies, and weaken configuration control. Furthermore, they disrupt digital continuity between PLM and Manufacturing Execution Systems, reducing confidence in the accuracy and completeness of torque data throughout the product lifecycle.

5. Instance-Based Torque Definition Model for High-Reliability Automotive Assemblies

To overcome the limitations of traditional part-based torque definition approaches, this paper proposes an instance-based torque definition model that associates torque specifications with individual fastener instances rather than with fastener references. This model enables torque requirements to be defined in direct alignment with the functional, safety, and manufacturing context of each joint. By embedding torque data at the instance level within the product structure, the proposed approach establishes a robust digital thread connecting engineering intent to manufacturing execution.

5.1 Conceptual Model and Design Principles

The instance-based torque definition model is founded on the distinction between part references and part instances within a Product Lifecycle Management (PLM) system. A part reference represents the master definition of a fastener, including its geometry, material, and part number. In contrast, a part instance represents a specific usage of that fastener within an assembly and captures contextual information such as position, orientation, and relational hierarchy.

In the proposed model, torque attributes are assigned to the fastener instance, which is uniquely identifiable within the assembly structure. Each instance is enriched with torque-related information, including joint identification, tightening strategy, torque and angle tolerances, and residual torque limits. This approach allows identical fastener references to support different torque requirements based on their application context, without duplicating part definitions or compromising configuration control.

5.2 Instance-Level Torque Attributes and Governance

To support high-reliability automotive assemblies, the instance-based model defines a standardized set of torque attributes associated with each fastener instance. These attributes typically include a unique joint identifier, joint criticality classification, torque strategy selection, target torque and tolerance, target angle and tolerance (where applicable), and residual torque verification limits.

Governance mechanisms are essential to ensure consistency and correctness of instance-level torque data. Automated rules and validations can be applied to control attribute editability based on lifecycle state, joint criticality, or user role. Additionally, revision-aware propagation ensures that torque definitions remain synchronized across design iterations while preserving historical data for traceability and audit purposes. This governance framework enables scalable adoption of instance-based torque management without introducing excessive administrative overhead.

5.3 Integration Across Engineering and Manufacturing Domains

A key advantage of the proposed instance-based torque definition model is its ability to support seamless integration across engineering and manufacturing domains. Torque attributes defined at the Engineering Bill of Materials (EBOM) instance level are propagated to the Manufacturing Bill of Materials (MBOM) and Bill of Process (BOP) through established traceability mechanisms within the PLM environment.

By maintaining one-to-one relationships between engineering and manufacturing instances, the model ensures that torque specifications remain context-aware throughout the manufacturing lifecycle. When integrated with Manufacturing Execution Systems (MES), instance-level torque data enables precise work instructions, real-time parameter validation, and detailed data capture during assembly. This closed-loop integration enhances process control, improves quality visibility, and supports compliance with safety and regulatory requirements.

6. End-to-End Torque Data Flow Across the Manufacturing Lifecycle

The effectiveness of an instance-based torque definition model depends not only on how torque data is authored, but also on how accurately and consistently it is propagated across the manufacturing lifecycle. In automotive production, torque requirements defined during engineering must be preserved and enforced through manufacturing planning and execution stages. This section describes how instance-level torque data flows seamlessly from engineering to manufacturing, enabling traceability, process control, and closed-loop quality management.

6.1 Torque Authoring at the Engineering Bill of Materials (EBOM) Level

In the proposed approach, torque specifications are authored at the fastener instance level within the Engineering Bill of Materials (EBOM). Each fastener instance is uniquely identified within the product structure and enriched with torque-related attributes such as joint identification, criticality classification, tightening strategy, and tolerance limits. Authoring torque data at this stage ensures that engineering intent is explicitly captured in the digital product definition rather than being embedded in external documents or drawings.

By associating torque data with individual fastener instances, engineers can account for contextual factors such as joint function, material combinations, and reliability requirements. This approach also supports consistent reuse of fastener references while allowing torque requirements to vary across different applications. As a result, the EBOM becomes the authoritative source for torque intent, forming the foundation for downstream manufacturing processes.

6.2 Propagation to Manufacturing Bill of Materials (MBOM) and Bill of Process (BOP)

Once torque data is defined at the EBOM level, it must be accurately transferred to manufacturing planning structures. This propagation is achieved through traceability mechanisms that maintain one-to-one relationships between engineering and manufacturing instances. When fastener instances are assigned from EBOM to MBOM, the associated torque attributes are carried forward without loss of context or fidelity.

The Manufacturing Bill of Materials (MBOM) represents how the product is assembled on the shop floor, while the Bill of Process (BOP) defines the sequence of manufacturing operations and the resources required. Instance-level torque data is linked to specific operations within the BOP, ensuring that torque requirements are aligned with the correct assembly steps. This integration allows manufacturing planners to define precise work instructions, tightening sequences, and tool requirements based on engineering-defined torque intent.

6.2.1 Role of 3DEXPERIENCE in Instance-Level Torque Management

The implementation of the proposed instance-based torque definition model is enabled by the 3DEXPERIENCE platform, which serves as an integrated Product Lifecycle Management (PLM) environment connecting design, engineering, manufacturing, and execution domains. Unlike traditional file-based PLM systems, 3DEXPERIENCE provides a unified data model in which product structures, manufacturing processes, and operational data are managed within a single digital context.

Within this environment, torque specifications are authored and governed as structured data rather than as annotations or external documentation. Engineering users define torque requirements at the fastener instance level within the Engineering Bill of Materials (EBOM), ensuring that torque intent is embedded directly into the product structure. The platform enforces a single source of truth, enabling real-time collaboration between design, manufacturing, and quality teams while maintaining configuration control across lifecycle stages.

3DEXPERIENCE further supports instance-level torque management through data model customization and lifecycle-aware governance. Torque attributes such as joint identification, tightening strategy, tolerances, and verification limits are stored on relationship objects representing fastener instances. Automated rules and validations ensure that torque data remains consistent, revision-aware, and aligned with joint criticality classifications. This capability forms the foundation for reliable downstream propagation of torque data across manufacturing planning and execution systems.

6.2.2 Scope and Implemented Links for EBOM–MBOM–BOP Traceability

Maintaining traceability between engineering and manufacturing data is essential for preserving torque intent throughout the product lifecycle. In the 3DEXPERIENCE platform, this traceability is achieved through the combined use of Scope Links and Implemented Links, which together define the relationship between EBOM, MBOM, and Bill of Process (BOP) structures.

A Scope Link establishes the authoritative source relationship between product structures. When creating a Manufacturing Bill of Materials (MBOM), the EBOM is explicitly scoped to the MBOM, indicating that the EBOM serves as the engineering source from which manufacturing structures are derived. Similarly, when defining a Bill of Process (BOP), the MBOM is scoped to the BOP to specify that manufacturing operations and part assignments originate from the MBOM. This scoping mechanism ensures that instance-level torque attributes authored in the EBOM remain context-aware as they flow into manufacturing domains.

Once the scope relationship is established, Implemented Links are used to assign individual EBOM part instances to corresponding MBOM and BOP elements. Each fastener instance in the EBOM maintains a one-to-one implemented link with its manufacturing counterpart, preserving instance-level torque attributes without ambiguity or duplication. This linkage enables precise traceability of torque specifications from engineering definition through manufacturing planning and execution.

By leveraging Scope and Implemented Links, the 3DEXPERIENCE platform provides a robust and traversable framework for managing instance-level torque data across EBOM, MBOM, and BOP structures. These links are accessible through standard platform APIs, enabling seamless integration with Manufacturing Execution Systems (MES) and supporting end-to-end digital continuity for high-reliability automotive assemblies.

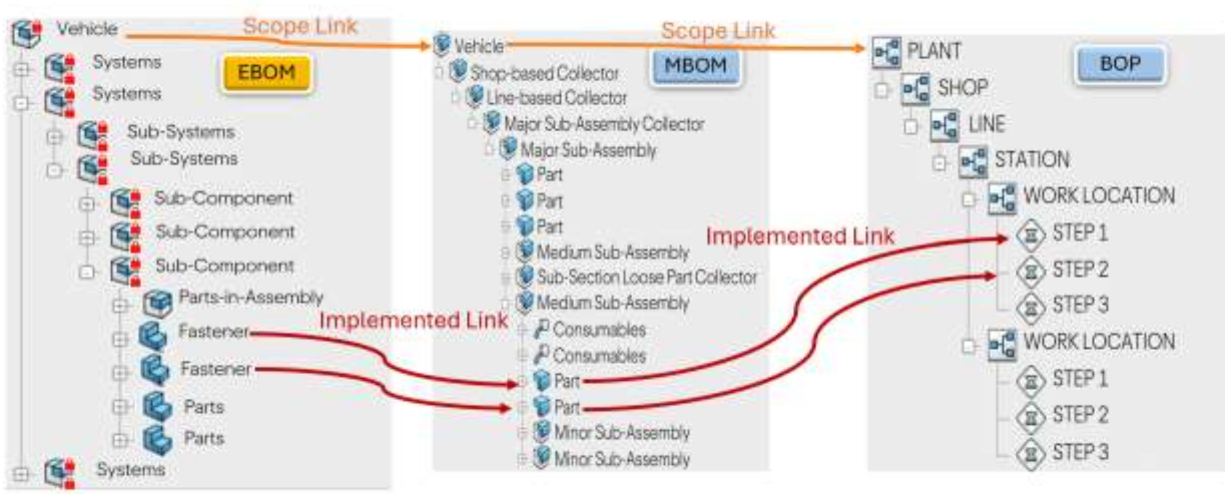

FIGURE 1. Image illustrating the Scope and Implemented link in PLM EBOM MBOM and BOP.

6.3 Integration with Manufacturing Execution Systems (MES)

The final stage of the torque data lifecycle occurs during manufacturing execution. Instance-level torque data propagated through MBOM and BOP is transferred to Manufacturing Execution Systems (MES) via system integrations. MES platforms use this data to guide assembly operations, enforce torque parameters, and capture tightening results in real time.

By leveraging instance-based torque definitions, MES can display context-specific torque values and strategies to operators, validate tool settings automatically, and record actual torque and angle measurements for each fastener instance. This capability enables detailed traceability, supports compliance audits, and facilitates rapid root-cause analysis when quality issues arise. Furthermore, the captured manufacturing data can be fed back into engineering systems to support continuous improvement and data-driven decision-making.

6.4 Practical Handling of Torque Workflow in 3DEXPERIENCE

In the 3DEXPERIENCE platform, torque management is handled as structured, instance-level product data that flows continuously from engineering design to manufacturing execution. Unlike traditional approaches where torque information is documented externally, 3DEXPERIENCE embeds torque requirements directly into the product structure and propagates them across engineering, manufacturing, and execution domains through a controlled digital workflow.

Step 1: Reference vs. Instance Concept in 3DEXPERIENCE

A fundamental concept underlying torque management in 3DEXPERIENCE is the clear separation between **part references** and **part instances**.

- A part reference represents the master definition of a component. It contains information such as part number, geometry, material, and design intent.
- A part instance represents a specific usage of that reference within an assembly or Bill of Materials. It captures contextual information such as position, orientation, and its relationship to other components.

In complex automotive assemblies, a single fastener reference may be reused hundreds of times. Although the reference remains the same, each instance corresponds to a different physical joint. Because torque requirements depend on joint location, function, and criticality, torque data is inherently instance-specific. For this reason, 3DEXPERIENCE associates torque attributes with the instance (relationship) rather than with the part reference.

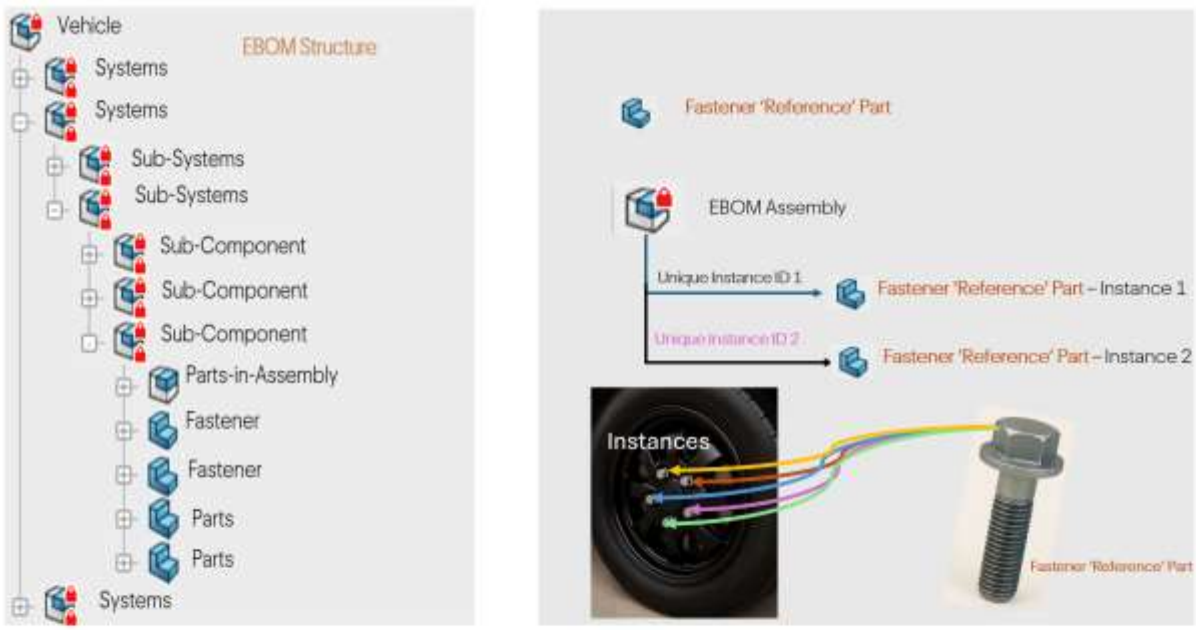

FIGURE 2. Image showing EBOM structure and difference in reference vs instance.

Step 2: Torque Definition During Design (CATIA → EBOM)

The torque workflow begins during the design and engineering phase. Fasteners are assembled within product structures created using design authoring tools, and these structures are managed within the Engineering Bill of Materials (EBOM).

For each fastener instance, engineers define torque-related attributes such as:

- Joint identification
- Joint criticality (critical, significant, non-critical)
- Torque strategy (target torque or torque plus angle)
- Torque and angle tolerances
- Residual torque verification limits

These attributes are stored on the instance relationship object, which uniquely identifies each fastener usage. By defining torque at this level, engineering intent becomes an explicit part of the EBOM rather than an implicit assumption or external note.

Lifecycle-based governance ensures that torque attributes are editable only at appropriate maturity stages, preserving data integrity as the design progresses toward release.

Step 3: Instance-Level Data Modeling and Governance

Each fastener instance in the EBOM is represented by a unique relationship identifier within the 3DEXPERIENCE data model. This identifier acts as the carrier of instance-level attributes, including torque data.

The platform supports:

- Automated generation of unique joint IDs
- Validation rules to ensure mandatory torque fields are populated
- Controlled editability based on lifecycle state and user role
- Revision-aware propagation of torque data

This governance framework allows identical fastener references to coexist with different torque definitions while maintaining configuration control and traceability.

Step 4: Propagation from EBOM to MBOM (Manufacturing Perspective)

Once torque data is authored in the EBOM, it must be transferred to manufacturing planning structures. The Manufacturing Bill of Materials (MBOM) represents how the product is assembled on the shop floor.

In 3DEXPERIENCE, the EBOM is explicitly defined as the source for the MBOM through a controlled scoping mechanism. This ensures that fastener instances, along with their associated torque attributes, are transferred to the MBOM without losing instance context.

Each EBOM fastener instance maintains a one-to-one relationship with its corresponding MBOM instance. As a result, torque data defined by engineering remains intact and traceable as manufacturing planning progresses.

Step 5: Association with Manufacturing Operations (MBOM → BOP)

The Bill of Process (BOP) defines the sequence of manufacturing operations required to assemble the product, along with the resources, tools, and work instructions used at each step.

When the MBOM is linked to the BOP:

- Fastener instances are assigned to specific assembly operations
- Torque attributes are associated with the correct tightening step
- Required tools and resources are identified

This association ensures that torque requirements are not only tied to parts, but also to the exact operation in which tightening occurs. As a result, manufacturing instructions reflect both what needs to be tightened and how it must be tightened.

Step 6: Execution on the Shop Floor (BOP → MES)

The final stage of the torque workflow is manufacturing execution. Torque data defined and propagated through EBOM, MBOM, and BOP is transferred to a Manufacturing Execution System (MES) via system integrations.

During production, the MES:

- Displays exact torque values and tightening strategies to operators
- Validates torque tool parameters before execution
- Captures actual torque and angle measurements for each fastener instance
- Records results for traceability, audits, and quality analysis

Because torque data remains instance-specific throughout the workflow, each tightening result can be traced back to a unique joint in the product structure.

Step 7: Closed-Loop Traceability and Feedback

The instance-based torque workflow enables closed-loop traceability across the entire manufacturing lifecycle. Engineering-defined torque intent, manufacturing execution data, and quality verification results are digitally connected.

This closed-loop capability supports:

- Rapid root-cause analysis
- Audit readiness for safety-critical assemblies
- Continuous improvement through data-driven insights

By maintaining torque data at the instance level from design to execution, 3DEXPERIENCE ensures that engineering intent is consistently realized on the shop floor.

7. Implementation Using 3DEXPERIENCE and DELMIA

The proposed instance-based torque definition model is implemented using a Product Lifecycle Management (PLM) platform integrated with digital manufacturing solutions. This implementation enables torque data to be authored, governed, and propagated across engineering and manufacturing domains while maintaining full traceability. The section describes how instance-level torque management is realized using PLM data modeling, configuration mechanisms, and system integrations.

7.1 Instance-Level Data Modeling and Attribute Definition

The implementation leverages instance-level relationship objects within the PLM system to store torque-related attributes. Each fastener instance is uniquely identified within the assembly structure and serves as the carrier for torque specifications. This approach avoids duplication of fastener part definitions while allowing torque requirements to vary by application context.

Table 1 summarizes the key torque-related attributes defined at the instance level and their functional purpose.

Table 1. Instance-Level Torque Attributes

Attribute Name	Description	Purpose
Joint ID	Unique identifier for each fastener instance	Traceability and audit reference
Joint Criticality	Classification (Critical / Significant / Non-Critical)	Strategy selection and governance
Torque Strategy	Target Torque or Torque + Angle	Tightening method definition
Target Torque (N·m)	Nominal torque value	Preload generation
Torque Tolerance (± N·m)	Acceptable torque range	Quality control
Target Angle (°)	Angular rotation after torque	Stretch control
Angle Tolerance (± °)	Allowable angle variation	Process robustness
Residual Torque Min/Max	Verification limits	Post-assembly validation

Attribute governance rules ensure that torque data is editable only at appropriate lifecycle stages and by authorized roles. Automated validations enforce completeness and consistency, particularly for safety-critical joints.

7.2 Configuration, Automation, and Change Management

To support scalable adoption, the implementation incorporates configuration and automation mechanisms that manage torque data throughout the product lifecycle. Automated processes generate unique joint identifiers, propagate torque attributes across revisions, and enforce consistency between engineering and manufacturing structures.

Change management is handled at the instance level, allowing torque updates to be applied selectively without affecting unrelated fastener usages. This capability significantly reduces the risk of unintended changes and improves configuration control in complex assemblies.

Table 2 outlines the key automation mechanisms used in the implementation and their objectives.

Table 2. Automation and Configuration Mechanisms

Mechanism	Function	Benefit
Joint ID Auto-Generation	Creates unique IDs during lifecycle transitions	Eliminates manual errors
Attribute Locking Rules	Controls editability by state and role	Data integrity
Revision-Aware Propagation	Maintains torque data across revisions	Traceability
Validation Rules	Ensures mandatory attributes are populated	Quality compliance

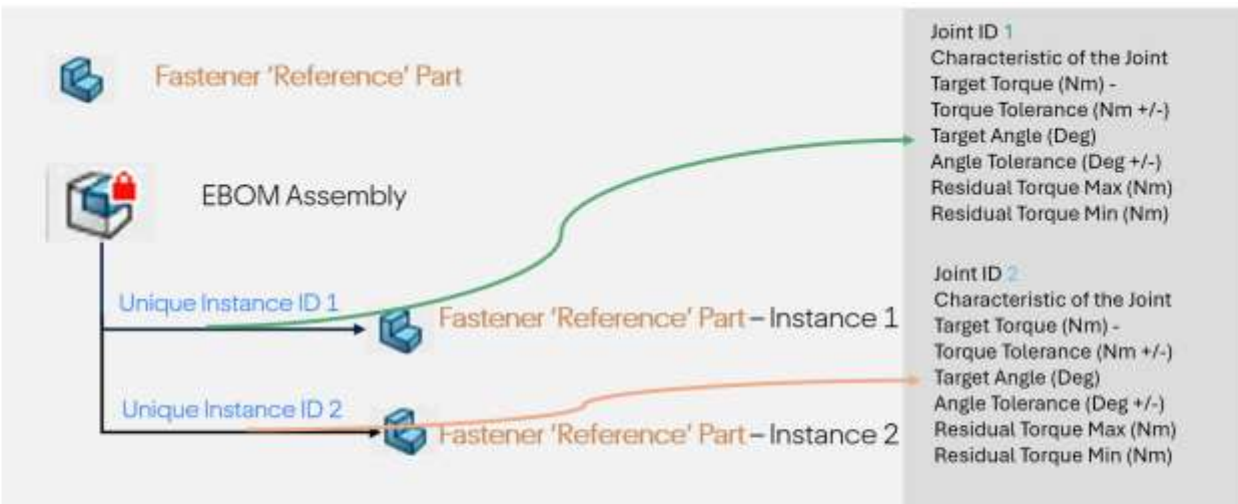

FIGURE 3: Image showing fastener instances and associated attributes.

7.3 Integration with Manufacturing Execution Systems

The final implementation layer involves integrating instance-level torque data with Manufacturing Execution Systems (MES). Data exchange is achieved through standardized interfaces that transfer BOM, process, and torque information from PLM to MES. This integration enables MES to execute manufacturing operations in direct alignment with engineering-defined torque intent.

During assembly, MES enforces torque parameters, validates tool settings, and captures actual torque and angle measurements for each fastener instance. The captured data is stored with instance-level identifiers, enabling detailed traceability and supporting downstream quality analysis. This closed-loop integration strengthens the digital thread across engineering and manufacturing, improving reliability and audit readiness.

8. Case Study: Instance-Based Torque Management in a High-Reliability Automotive Assembly

To illustrate the practical applicability and benefits of the proposed instance-based torque definition model, this section presents a representative case study based on a high-reliability automotive assembly. The case study demonstrates how instance-level torque definitions improve traceability, manufacturing accuracy, and quality assurance when compared to traditional part-based torque management approaches.

8.1 Assembly Description and Problem Context

The selected case involves a high-reliability automotive powertrain subassembly, consisting of multiple structural and functional components secured using threaded fasteners. Several identical fastener references are reused across the assembly to attach components such as bearing caps, covers, and structural brackets. Although the fasteners share the same geometry and material, their functional roles and reliability requirements differ significantly based on their location within the assembly.

Under a traditional part-based torque definition model, a single torque specification was associated with each fastener reference. This approach resulted in challenges during manufacturing and quality verification, particularly for joints requiring torque-plus-angle tightening and residual torque validation. Manufacturing teams relied on supplemental work instructions and manual checks to differentiate between fastener applications, increasing the risk of inconsistency and rework.

8.2 Application of the Instance-Based Torque Definition Model

Using the proposed instance-based torque definition model, torque specifications were authored at the fastener instance level within the Engineering Bill of Materials (EBOM). Each fastener instance was assigned a unique joint identifier and enriched with torque attributes reflecting its specific functional context. Critical joints were defined using torque-plus-angle strategies with strict tolerance limits, while non-critical joints employed target torque strategies with broader tolerances.

These instance-level torque definitions were propagated to the Manufacturing Bill of Materials (MBOM) and Bill of Process (BOP), where they were associated with specific assembly operations. Manufacturing Execution Systems (MES) received the instance-level torque data and used it to guide tightening operations, validate tool settings, and capture actual torque and angle values during assembly. This ensured that each fastener was tightened according to its specific engineering intent without relying on manual interpretation.

8.3 Observed Benefits and Outcomes

The adoption of the instance-based torque definition model resulted in measurable improvements across engineering, manufacturing, and quality domains. Manufacturing rework related to incorrect torque application was significantly reduced, as operators received clear, context-specific instructions directly from MES. Instance-level traceability enabled rapid identification of affected joints during quality investigations, improving response time and containment effectiveness.

From an engineering perspective, torque changes could be applied selectively to individual fastener instances without impacting unrelated applications, improving configuration control and reducing data maintenance effort. Quality teams benefited from detailed torque and angle records linked to specific joint identifiers, supporting audit readiness and compliance requirements. Overall, the case study demonstrated that instance-based torque management enhances reliability, traceability, and operational efficiency in high-reliability automotive assemblies.

9. Discussion and Benefits

The instance-based torque definition model presented in this paper represents a shift from traditional, part-centric torque management toward a more context-aware and digitally integrated approach. By embedding torque specifications at the fastener instance level and propagating them across the manufacturing lifecycle, the proposed model addresses several long-standing challenges in automotive manufacturing. This section discusses the key benefits and broader implications of adopting instance-based torque management in high-reliability assemblies.

9.1 Improved Torque Accuracy and Assembly Reliability

One of the primary benefits of instance-based torque definition is the improved alignment between engineering intent and manufacturing execution. By defining torque strategies, tolerances, and verification requirements at the instance level, each fastener is tightened according to its specific functional and reliability requirements rather than a generalized part-level specification. This approach reduces the risk of over-tightening or under-tightening, particularly in assemblies where identical fasteners serve different roles.

For high-reliability joints such as powertrain and suspension fasteners, the ability to precisely apply torque-plus-angle strategies and enforce strict tolerance limits leads to more consistent joint preload. This consistency directly improves joint durability, reduces the likelihood of preload loss over time, and enhances overall vehicle reliability. The instance-based model therefore supports both immediate assembly quality and long-term product performance.

9.2 Enhanced Traceability, Quality Control, and Compliance

Instance-level torque management significantly strengthens traceability across engineering, manufacturing, and quality domains. Each fastener instance is uniquely identifiable, allowing torque specifications and actual tightening results to be directly linked to a specific joint location. This granularity enables detailed tracking of torque application throughout the production process and supports rapid root-cause analysis when quality issues arise.

From a compliance perspective, the availability of instance-level torque data improves audit readiness for safety-critical assemblies. Regulatory and customer audits often require proof that specified torque strategies were correctly applied and verified. The proposed model provides a digital record of torque and angle values captured during manufacturing, eliminating reliance on manual documentation and reducing audit effort. As a result, quality teams gain greater confidence in both process control and data integrity.

9.3 Operational Efficiency and Digital Lifecycle Integration

Beyond quality improvements, the instance-based torque definition model delivers tangible operational benefits. Engineering changes to torque specifications can be applied selectively to individual fastener instances without impacting unrelated applications, reducing rework and minimizing disruption to manufacturing operations. This targeted change management improves configuration control and lowers the cost of maintaining complex product structures.

The model also strengthens digital continuity across the product lifecycle by enabling seamless integration between PLM, digital manufacturing systems, and MES. Torque data flows consistently from design to execution, supporting closed-loop manufacturing and data-driven continuous improvement. As automotive manufacturers increasingly adopt digital twins and advanced analytics, instance-level torque data provides a valuable foundation for future enhancements such as predictive quality monitoring and optimization of fastening processes.

10. Conclusion and Future Work

This paper presented an instance-based torque definition model designed to address the limitations of traditional part-based torque management approaches in high-reliability automotive assemblies. By associating torque specifications with individual fastener instances rather than fastener references, the proposed model enables context-aware torque definition, improved traceability, and stronger alignment between engineering intent and manufacturing execution.

The paper demonstrated how instance-level torque data can be authored within the Engineering Bill of Materials (EBOM) and propagated seamlessly across the Manufacturing Bill of Materials (MBOM), Bill of Process (BOP), and Manufacturing Execution Systems (MES). Through this end-to-end digital workflow, torque strategies, tolerances, and verification requirements are preserved throughout the manufacturing lifecycle. The case study illustrated that this approach leads to improved torque accuracy, reduced rework, enhanced quality visibility, and greater audit readiness for safety-critical automotive assemblies.

From an operational perspective, the instance-based model supports efficient change management by allowing torque updates to be applied selectively without affecting unrelated fastener applications. This capability reduces data complexity, strengthens configuration control, and improves overall manufacturing efficiency. Furthermore, the integration of instance-level torque data with digital manufacturing systems establishes a robust digital thread that supports closed-loop quality management and continuous improvement initiatives.

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