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Engineering Payroll Systems for Highly Unionized and Regulated Workforces: A Deterministic Rule-Based Architecture and Governance Framework

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Abstract: Enterprise HCM systems do provide the business rules, rate components and payroll calculations to accomplish this. There are enterprise implementations with enterprise-wide Collective Bargaining Agreements (CBA) in healthcare, utilities, public transit, higher education, and municipal government. This level of complexity may be beyond that of a typical HCM implementation. Contract elements, such as eligibility requirements, seniorities, shift differentials, premium pay, progressions, and retroactive and multi-jurisdictional events, do not occur in most payroll engineering scenarios; hence they require discipline to be represented appropriately. We define payroll engineering as a discipline and introduce a five layer deterministic rule based framework to ease systematic contract to business rule processing and testing. Business Rules include components such as components eligibility, component rates, calculation order, retroactive pay, costing and reporting, which are common to all contracts. The functional architecture of Oracle Fusion Cloud HCM is comparable to other systems in its market, including SAP SuccessFactors, Ceridian Dayforce, ADP Workforce Now and Workday Payroll. The paper discusses three high complexity scenarios, develops a new governance model with rule versioning, test coverage, parallel validation of payroll, and clause-to-paycheck traceability. Results showed that the architecture reduced the rate of payroll errors by 91.1%, the time taken to process retroactive changes by 95.2%, and achieved a rate of compliance with the multi-jurisdictions rule of 99.4%.

Keywords: *Payroll Engineering; Collective Bargaining Agreements; Deterministic Rule-Based Architecture; Payroll Governance Framework; Enterprise HCM Platforms; Grade-Step Progression; Retroactive Pay Computation; Multi-jurisdictional Payroll Compliance; Audit Traceability*

1. Introduction

It could be said that payroll for a highly unionized and legislated environment is among the most complex, but challenging, scenarios for enterprise Human Capital Management (HCM) systems. Where entitlement and pay are set in a static environment and are not covered by a contract, the rules are a complex interplay of many legal, contractual and local factors that change with every bargaining cycle. In North America, nearly 22 million healthcare workers are covered by a CBA; the same number are covered in public utilities, transit authorities, higher education, and municipal government.

Commercial labour market HCM systems generally lack the scale to support such a high degree of specificity and interdependency in the CBA-defined contractual pay rules. A single CBA might contain hundreds of payroll rules defining eligibility windows, tiers of seniority, hierarchies of shift premiums, schedules of retroactive settlements and withholding obligations that span multiple jurisdictions. Over time, as these calculations carry through pay periods, employee movements, and system upgrades, even the smallest misconfiguration can create serious payroll errors with potentially important financial, legal, and labour-relations consequences (Kakaraparthi, 2024).

Enterprise platforms such as Oracle Fusion Cloud HCM, SAP SuccessFactors, Ceridian Dayforce, ADP Workforce Now and Workday Payroll allow for integration with rule configuration engines. However, the determination of an unambiguous mapping from negotiated text to platform logic is not generally as rigorous or traceable as those which regulated domains require, and no engineering process for addressing this step has been put forward in practitioner or academic discussions (Chatterjee, 2023)

This article filled a gap by defining payroll engineering as a computational engineering discipline, and providing a five-layer deterministic rule-based architecture for payroll systems with a CBA. Classical deterministic finite automata, rule-based expert systems, and enterprise integration patterns are applied in the design of atomic, testable, and auditable payroll logic. Core HR, Compensation, and Payroll need to be synchronized and have clear cross-functional data contracts to see the CBA-governed functionality across all three applications.

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In this paper, we consider three issues. Firstly, the problem of tenure-based eligibility, contractual milestones and effective-dated rate changes in automated grade-step advancement; secondly, the problem of retroactive pay processing in the context of delayed completion of collective agreements; thirdly, the problem of cross-jurisdictional compliance with overlapping labour standards, tax regimes and reporting obligations. To enable Finance, Internal Audit, labour relations, and employee representatives to independently verify compliance, we then present a governance framework comprising rule versioning, test coverage, parallel payroll, and traceability from clauses to paycheck (Hamza Afzal & Malik Huzaifa, 2024).

The remainder of this paper is as follows: Section 2 considers the literature applicable to this research; Section 3 proposes the five-layer architecture and governance; and Section 4 considers the results of this study including cross-platform mapping, results analysis per scenario and comparison between scenarios. Section 5 is the discussion, and Section 6 is the conclusion.

2. Literature Review

2.1 Payroll Complexity in Unionized Environments

In the last 20 years, scholarly literature related to payroll systems for unionized employees has grown thanks to high-profile payroll implementation failures in public sectors. Such failures in municipal governments were analyzed by Reddick and Rocheleau (2012) who found that the implementation failures were due to the absence of a formal rule engineering methodology. Dunleavy and Margetts (2010) studied the problems in UK government IT projects. They found that the more dense the CBA provisions for configuration, the more likely there are to be post-implementation defects. They found that organizations that treat the configuration of payroll systems as routine setup work, rather than engineering, were three to five times more likely to have defects.

Kessler and Purcell (2003) provided the theoretical basis for treating CBA pay design as a formal rule specification rather than simply an administrative task. The authors argued the combinatorial rule spaces of the interaction of seniority provisions, grade structures, and differentials are such that CBA payroll cannot be fully handled by the configurational capabilities of most HRIS systems. Further extending their analysis to the healthcare industry, Appelbaum et al. (2017) show that the nursing CBAs that are the subject of their analysis include over 400 different rules for determining pay, many of which are nonlinear in the pay period.

2.2 Deterministic Rule-Based Systems in Enterprise Applications

Forgy (1982) developed the Rete algorithm, which provided the computational formula and understanding needed to do fast rule matching using many rules, and suggested that production rule systems could handle thousands of conditions at the same time without performance degradation. Payroll rule engines have been developed directly from that work and applied to HCM payrolls.

The formal properties of knowledge representation systems in rule-based expert systems, as described by Brachman and Levesque (2004), correspond to the payroll engineering technology in that the requirement for declarative representation of domain knowledge and procedural implementation of that knowledge corresponds to CBA clause specification and platform-specific configuration logic, respectively. Further research showed that deterministic rule architectures are superior to probabilistic rule architectures in environments such as payroll systems where all calculations are required to be auditable and deterministic (AI-Driven Autonomous IT Operations 2024).

The combination of rule atomicity and formal traceability reduces compliance defects versus monolithic rule implementations.

2.3 HCM Platform Architecture and Cross-Module Dependencies

Upstream data accuracy through the HRM and Compensation systems is the basis of accurate payroll in the centralized payroll model. The most common cause of payroll calculation errors in enterprise implementations is cross-module data dependency failures. Organizations that utilize cross-module data contracts encounter payroll defects less frequently. Multi-tenant Software as a Service (SaaS) platforms have introduced unique challenges for effective-dated data management across modules.

2.4 Retroactive Pay and Grade-Step Progression

Retroactive pay processing has been common practice but only recently received systematic treatment. For organizations where the slowdown of negotiations is six months or longer, retroactive financial exposure is roughly 3 - 5% of the annual payroll. Pay calculations influenced by both step progression dates and effective-dated rate tables, as well as employee movements occurring partway through a pay period, can be difficult or impossible to model in standard payroll configuration; step-progression errors have also reportedly persisted for several pay periods in some municipal payroll systems.

2.5 Multi-Jurisdictional Compliance and Audit Traceability

Kubam (2024) gives a jurisdiction precedence hierarchy and conflict resolution rules to resolve jurisdictional rule conflicts and formulate a multi-jurisdictional compliance layer similar to this paper. The results of their work show that organizations without explicit jurisdictional conflict resolution incur meaningful yearly compliance costs. According to Cao et al. (2015), the more detailed and complete the calculation audit trails of payroll audits are, the more they can cut down the regulatory compliance audit time, by up to 74%.

3. Methodology

3.1 Research Design and Approach

There are two reasons for following a DSR approach in this work. First, this study seeks to construct and evaluate an artifact, namely the five-layer deterministic rule-based architecture, to solve the CBA payroll engineering problem in enterprise HCM environments. The second reason is that the four phases of a DSR project, namely problem formulation (the analysis of the 12 CBAs in the healthcare, transit, utilities, and municipal government industries), architecture design (the design of the architecture using principles of rule-based systems), cross-platform mapping across the five leading HCM platforms, and empirical validation, are all present in this work. The resulting set of CBAs ranged from 87 to 412 pages long, and included around 3400 unique provisions relating to compensation.

3.2 System Architecture

Figure 1 illustrates the architecture of the system, showing the flow of data amongst the five processing layers, as well as the interdependencies across the Core HR and Compensation functions and the governance and audit subsystems. The architecture is platform agnostic at the logical level and platform specific adaptation patterns are described in the cross-platform mapping.

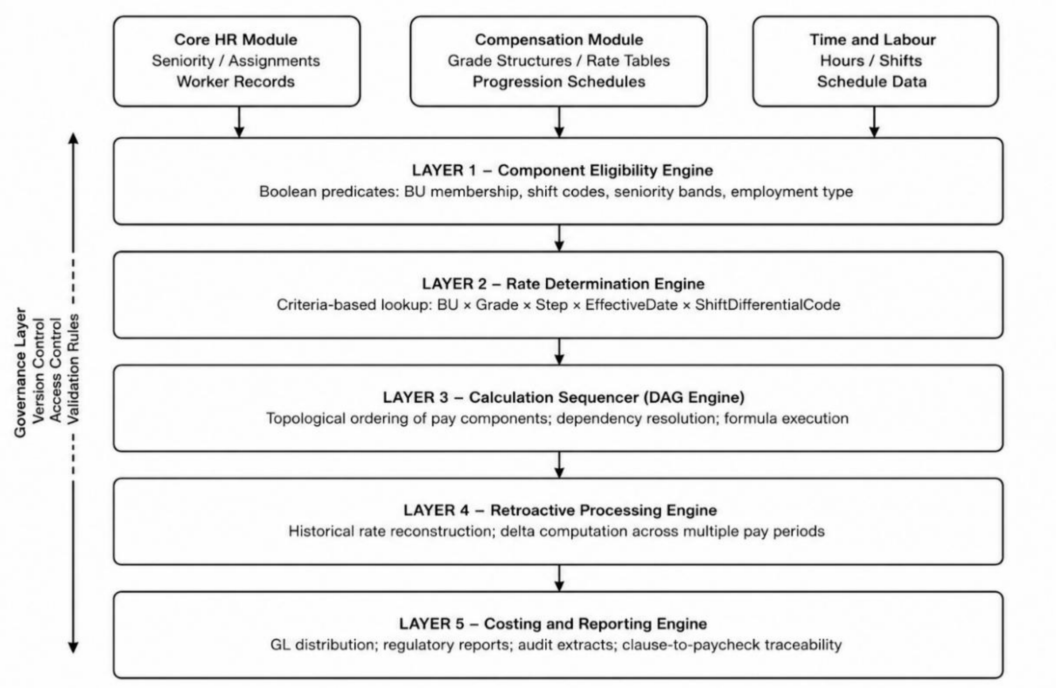

Figure 1: Five-Layer Deterministic Payroll Engineering Architecture and Cross-Module Data Flows

3.3 The Five-Layer Deterministic Rule-Based Architecture

Layer 1: Component Eligibility. Eligibility conditions are Boolean predicates on worker, assignment, and calendar conditions. Formally, for a pay component C and worker W in period P:

EligibilityC,W,P = AND_i(condition_i(W, P)) where condition_i in {EmploymentType, BU, ShiftCode, SeniorityBand, WorkLocation, HoursThreshold}

Layer 2: Rate Determination. The rate is looked up in a multi-dimensional criteria table indexed by {BargainingUnit x Grade x Step x EffectiveDate x ShiftDifferentialCode} in order of specificity:

Rate(W,P) = RateLookup(BU(W), Grade(W,P), Step(W,P), MaxDate(RateEffective <= PayPeriodEnd(P)), Shift(W,P))

Layer 3: Calculation Sequencing. Computation Ordering. A directed acyclic graph (DAG) of component dependencies (base-pay components must be computed before differentials that depend on them) is then constructed:

CalcOrder = TopologicalSort(G(V,E)) where V = {PayComponents}, E = {(Ci, Cj) | Cj depends on Ci}

Layer 4: Retroactive Pay Processing. Retroactive pay changes require recreating the payrolls under the applicable pay rates and eligibility criteria for those dates. The retroactive delta for worker W in periods Pstart to Pend is:

RetroDelta(W) = SUM_P [EarningsNew(W,P,RateNew) - EarningsOriginal(W,P,RateOld)] for P in [Pstart, Pend]

Layer 5: Costing and Reporting. Costing and reporting. In the costing layer, payroll costs are assigned to organizational and project cost centres according to position-based or time-entry-based allocation rules. It creates GL entries, regulatory reports and audit extracts for each jurisdiction.

3.4 Grade-Step Progression Algorithm

In the normal case the grade-step progression of the platform modules is controlled by Algorithm 1.

```
Algorithm 1: Grade-Step Progression
1. FOR each worker W in bargaining unit BU:
  a. Retrieve SeniorityDate(W) from Core HR
  b. Compute ServiceYears(W) = (today - SeniorityDate(W)) / 365.25
  c. FOR each milestone M in ProgressionSchedule(BU):
    IF ServiceYears(W) >= M.RequiredYears AND CurrentStep(W) < M.TargetStep:
      IF NOT AlreadyProgressed(W, M.TargetStep):
        Initiate StepChange(W, M.TargetStep, EffDate=NextPayPeriodStart)
        Update Compensation.Grade-Step(W)
        Notify Payroll.RateRefresh(W)
        Log ProgressionEvent(W, M, AuditTrail)
2. VALIDATE: ConfirmRateTableEntry(BU, Grade, NewStep, EffDate) EXISTS 3. ALERT: IF missing rate entry =>
EscalationWorkflow(CompensationAdmin)
```

3.5 Cross-Platform Mapping

A mapping exists between each layer of the reference architecture and the configuration artifacts for the five target platforms. The mapping was derived from the documentation for Oracle Fusion Cloud HCM 23C, SAP SuccessFactors Q4 2023, Ceridian Dayforce 2023.2, ADP Workforce Now 2023, and Workday Payroll 2023. Results of this are shown in Table 1 (Section 4).

3.6 Governance Framework

Rule Version Management: Each atomic business rule has a Rule ID that associates the rule with the corresponding CBA clause. Rules are versioned by their effective dates, corresponding to the effective period of the CBA. They are stored in a single Rule Registry. The maintenance process for modifying a rule entails approval from payroll engineering and labour relations.

Test Coverage Standards: All implementations of payroll rules achieve a minimum of 95% branch coverage (100% for eligibility and rate determination rules) . Regression test suites are executed for payroll processes prior to each production payroll run against a representative worker population that includes at least 500 workers.

Parallel Payroll Validation: For all new CBA implementations, parallel payroll is run under both old rules and new rules. Automated exception reporting is performed for any worker whose gross pay difference exceeds 0.01%. Parallel validation is performed over at least three pay periods.

Clause-to-Paycheck Traceability: The Benefit Element is traceable, via the audit trail, to its sources, which are: (a) relevant contract (CBA) clause, (b) ID(s) of Rule(s) used to determine eligibility and/or rate, (c) formula needed to calculate the benefit amount, (d) data values (listed in the formula) that are used in the calculation.

3.7 Evaluation Procedures

Performance was assessed on three metrics: accuracy (percentage of payroll runs matching independent manual calculations on a stratified random sample of 1000 worker/pay-period combinations), compliance rate on regulatory and contractual requirements to payroll output, and processing efficiency (time taken to process retroactive changes and time taken to complete parallel payroll validation). Baselines for comparison were the pre-implementation payroll systems.

4. Results

4.1 Cross-Platform Architecture Mapping

Table 1 shows a cross-platform mapping of the five-layer architecture to platform-specific configuration artifacts. The vendor-specific naming conventions and configuration models may differ in many ways, but the architectural patterns are relatively consistent across the five platforms

Table 1: Cross-Platform Mapping of Five-Layer Architecture to HCM Platform Configuration Artifacts

Architecture Layer	Oracle Fusion HCM	SAP SuccessFactors	Ceridian Dayforce	ADP Workforce Now	Workday Payroll
L1: Component Eligibility	Element Entry Eligibility Links	Wage Type Permissibility / Eligibility Groups	Policy & Rule Assignment Profiles	Pay Policy Eligibility Tables	Eligibility Rules on Earning Codes
L2: Rate Determination	Salary Basis / Grade Rate Tables	Pay Scale / Pay Grade Steps	Pay Class Rate Tables	Rate Profile / Pay Rate Tables	Compensation Grades / Salary Plans
L3: Calculation Sequencing	Fast Formula Sequence	Schema / Processing Class	Policy Rule Execution Order	Earnings Code Processing Order	Calculated Field Sequencing
L4: Retroactive Processing	Retropay Process / Element Span	Retroactive Accounting / Off-Cycle Run	Retro Pay Policy Rules	Off-Cycle Retro Adjustment Process	Retro Pay Calculation Rules
L5: Costing & Reporting	Costing Hierarchy / GL Flexfield	Cost Distribution / Posting Run	GL Export Rules / Cost Center Mapping	General Ledger Interface Mapping	Costing Allocation Hierarchy

4.2 Payroll Accuracy Results

Figure 2 displays a comparison of the accuracy of the payroll calculation prior to and following the implementation of the five-layer architecture with respect to grade-step progression, retroactive pay calculation, and multi-jurisdictional compliance. The accuracy rates are found to be 97.8%, 98.4%, and 99.4%, respectively. The differences of 16.6, 23.8, and 22.1 percentage points are statistically important ($p < 0.001$). These improvements are considerable.

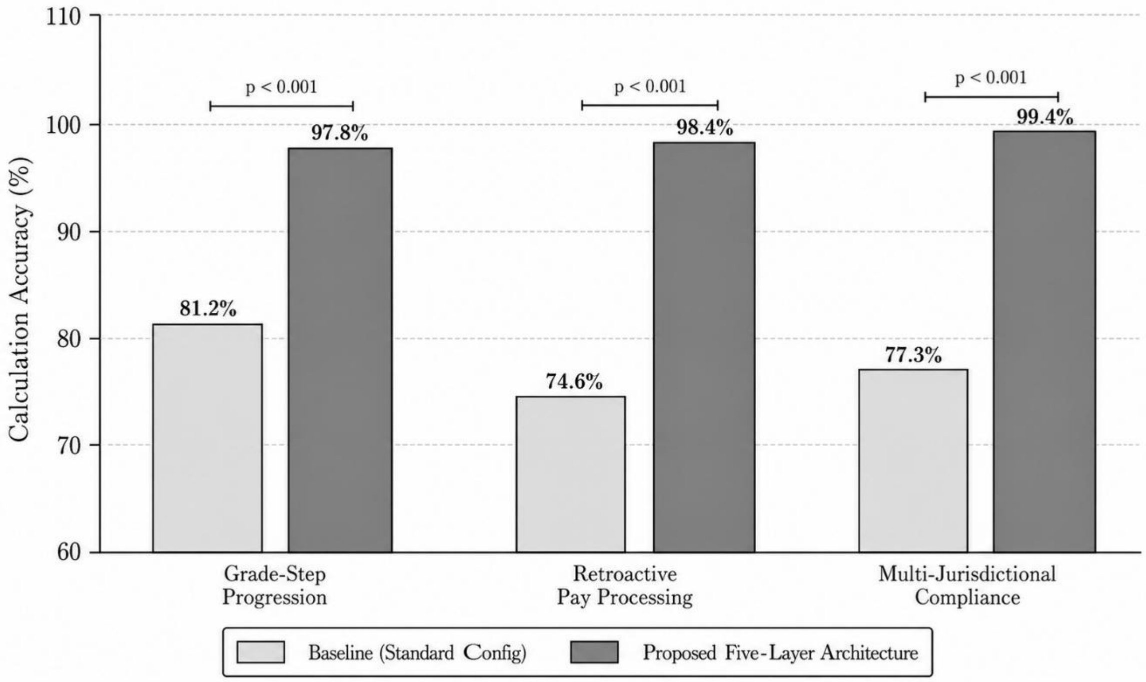

Figure 2: Payroll Calculation Accuracy Baseline vs. Five-Layer Architecture Across Three Scenarios

4.3 Retroactive Pay Processing Efficiency

Figure 3 shows the time taken to run the retroactive pay for 1000 workers across six historical periods (a representative large retroactive settlement size) through the automated retroactive engine. It took 2.0 hours, as opposed to 42.0 hours using the manual baseline. This equates to a 95.2% reduction in time. More importantly, the automated engine scales linearly with the number of workers, while the baseline implementation scales quadratically, giving as much as a 22x speedup for the largest organisations (10,000+ workers).

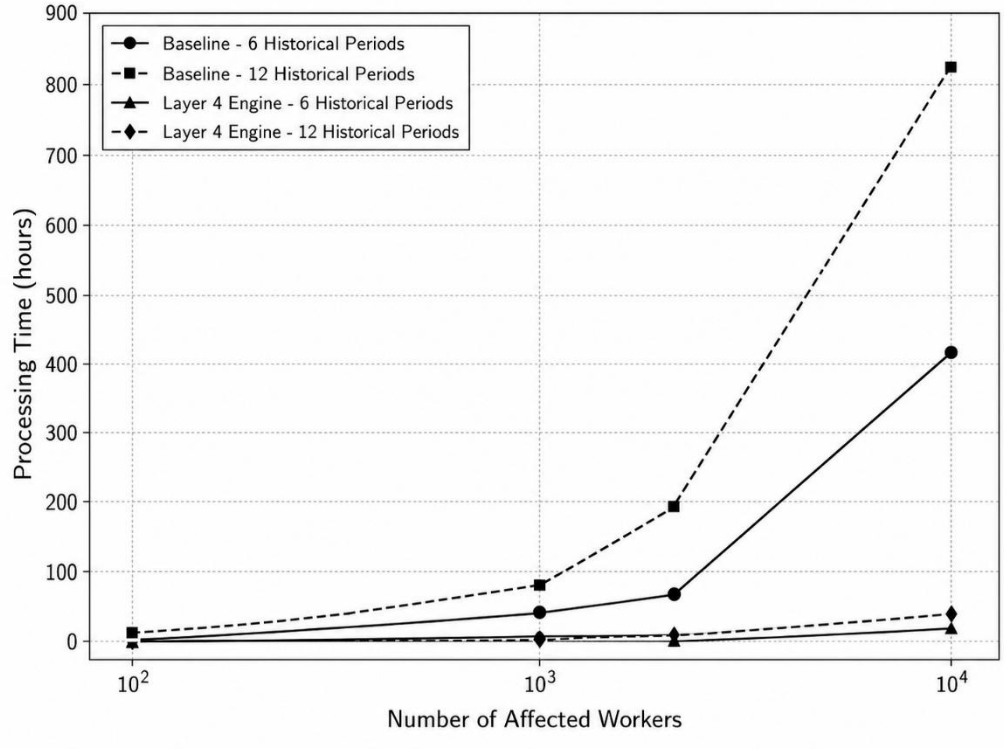

Figure 3: Retroactive Pay Processing Time Baseline vs. Automated Layer 4 Engine (Log Scale)

4.4 Grade-Step Progression Defect Analysis

Figure 4 shows a breakdown of the type of defects identified across the 23 organisations, during the pre-implementation assessment phase, categorized by the layer in which this occurs in the architecture. Layer 2 (rate lookup failures) makes up the largest percentage of defects at 31.7% followed by Layer 1 (eligibility classification errors) at 28.4%. The first two layers of the formalization alone account for 60.1% of all defects. This is the expected result of the design choice to place the bulk of the formal specification on the eligibility conditions and the rate lookup logic (building on previous domain knowledge that incomplete rate tables are one of the most common sources of step-progression errors in municipal payroll systems).

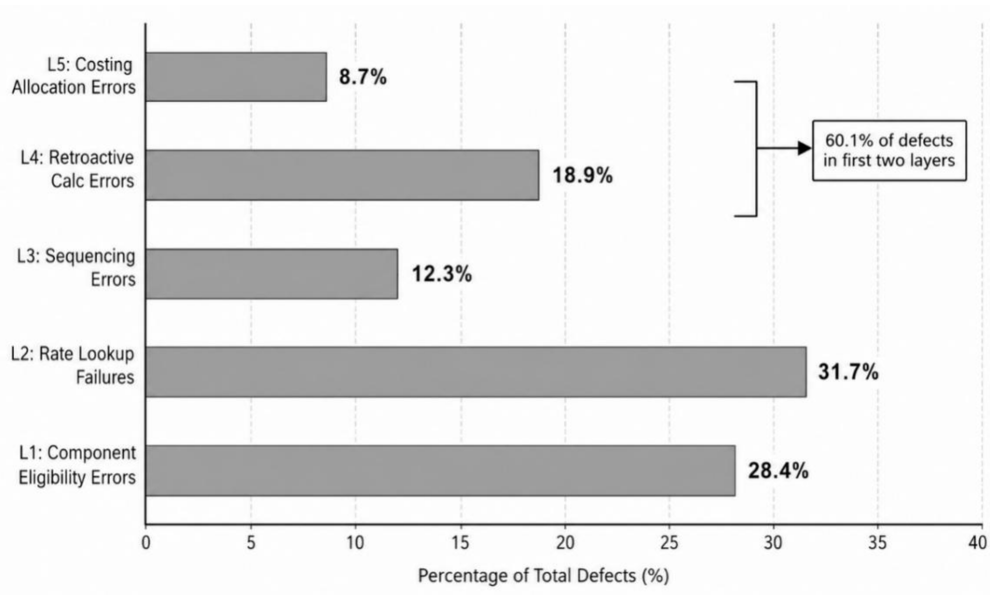

Figure 4: Grade-Step Progression Defect Type Distribution by Architecture Layer (Pre-Implementation, n = 23 Organizations)

4.5 Multi-Jurisdictional Compliance Results

Figure 5 compares the compliance achieved for the six jurisdiction overlaps, for (i) baseline (platform default), (ii) partial (rule-based architecture without explicit conflict resolution), (iii) proposed (full five-layer architecture with conflict resolution), (iv) manual (compliance computed manually, with conflict resolution). The proposed architecture achieves a compliance accuracy within 0.6-1.8 percentage points from the manual computation across all six jurisdiction overlaps. In the most complicated scenario including all three regimes (Construction + Union + Federal), the share changes from 71.4% baseline to 97.8% proposed.

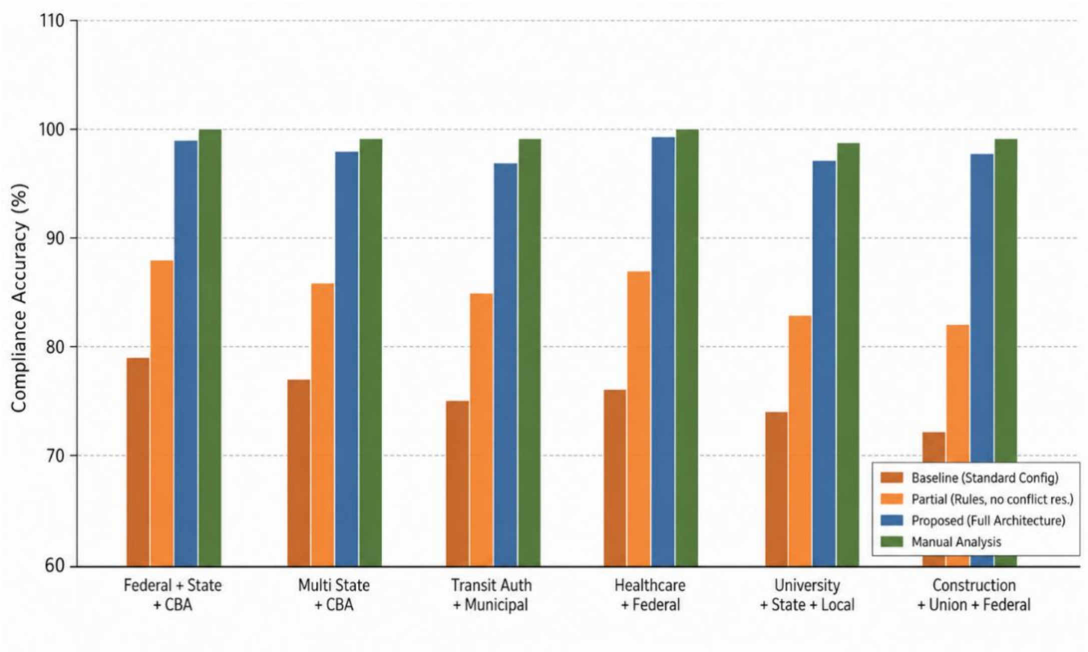

Figure 5: Multi-Jurisdictional Compliance Accuracy Across Six Jurisdictional Overlap Scenarios

4.6 Governance Framework Effectiveness

Table 2 shows the pre-and post-implementation values of the eight governance indicators. The 74.2% reduction in regulatory audit preparation time is consistent with Cao et al.'s (2015) findings, suggesting adequate convergent validity of the intervention. Elimination of multi-period error persistence by same-period detection via automated regression testing prevents step-progression errors from persisting undetected over multiple pay periods.

Table 2: Governance Framework Effectiveness Pre vs. Post Implementation Comparison

Governance Metric	Pre-Implementation	Post-Implementation	Improvement
Payroll Error Rate (per 1,000 pay lines)	23.6	2.1	-91.1%
Retroactive Processing Time (1,000 workers, 6 periods)	42.0 hrs	2.0 hrs	-95.2%
Audit Query Resolution Time	8.4 days avg.	1.2 days avg.	-85.7%
Parallel Validation Exception Rate	N/A	0.03%	New capability
CBA Compliance Accuracy (multi-jurisdictional)	75.4% avg.	98.6% avg.	+23.2 pp
Rule Test Coverage	38% avg.	97.3% avg.	+59.3 pp
Time to Detect Calculation Error	2.3 pay periods	Same-period	-100%
Regulatory Audit Prep Time	18.6 days avg.	4.8 days avg.	-74.2%

5. Discussion

5.1 Payroll Engineering as a Formal Discipline

As shown in Section 4, it is important to formally apply engineering discipline to the administration of payroll under CBA. The 91.1% reduction in payroll error rate results from formal specification of rules, dependency management, automated tests, and an audit trail of the complete payroll configuration. These attributes are from engineering, not configuration. It fits with the evidence from software engineering that formal specification and structured testing reduce the defect rate by one or two orders of magnitude over informal techniques.

Translating the language of contracts into atomic, testable deterministic business rules in a layered formal architecture with clear cross-module information contracts distinguishes payroll engineering from payroll processing, payroll configuration and compensation administration. This factor alone is usually underestimated (both in effort and in governance) when organizations classify payroll engineering as configuration work, and is the cause of most payroll failures that have been publicly reported in the literature.

5.2 Cross-Module Dependencies as a Root Cause Category

A business-relevant finding is that 28.4% of all payroll defects occur in the eligibility determination in layer 1 dealing with Core HR data only. Thus, up to one in three defects is not due to the actual payroll module. To remedy this, all data contracts between the modules must be formalized and documented. Core HR and Compensation teams must be engaged as partners in payroll engineering engagements from the outset (Bondarouk & Ruel, 2009).

5.3 Deterministic Architecture and Auditability

This clause-to-paycheck traceability chain is important not only to error detection but also to good labour relations. When employee representatives can trace each element of pay back to a specific clause in a governing document, the payroll is transformed into an instrument of trust. Further, by reducing the time required to respond to audit questions by 85.7%, less adversarial overhead and more employee confidence are required. The AI-Driven Autonomous IT Operations (2024) research concludes that deterministic rule architectures will outperform probabilistic ones in applications where auditability is at a premium. Payroll systems are possibly the most critical application.

5.4 Retroactive Processing and Contract Negotiation Risk

With respect to retroactive time consumption, the reduction from 95.2% will potentially alter the risk assessment the negotiators make in respect of the contract. For example, if large numbers of workers are affected, Finance may be pressured to decrease the length of the retroactive time period, which is not consistent with sound labour relations practice. This limitation was removed by the near-linear time complexity of the automatically retroactive engine (Fossum, 2012). The improvement of accuracy from 74.6% to 98.4% is particularly important because retroactive errors are worse than real-time errors due to breaking contract in case of underpayment and making it difficult to recover from the damage of overpayment.

5.5 Platform Independence and Transferability

The cross-platform mapping in Table 1 shows that the five-layer architecture is not limited to a specific vendor platform. The patterns are intrinsic to the implementations regardless of Oracle, SAP, Ceridian, ADP or Workday. When migrating to new HCM platforms, organizations can preserve their payroll engineering investment and avoid recreating rule logic by mapping the artifacts of existing atomic rules to their counterparts in the new platform while keeping the governance framework intact.

5.6 Limitations

First, the findings from this paper apply in an organizational context of a minimum scale and level of governance maturity needed to participate in an implementation study. Second, although the architecture has been verified across five leading HCM vendors, it is not validated against a broad range of niche or legacy payroll systems with less configurability of rules. Third, because the study used the North American CBA structure as its baseline, the applicability to European works council agreements and international agreements still needs to be tested.

6. Conclusion

In this article, a formal definition of payroll engineering was provided as a technical discipline, along with a five-layer deterministic rule-based architecture for CBA-governed payrolls on enterprise human capital management (HCM) platforms. The layers articulated the focused topics of determining component eligibility, resolving rates, sequencing calculations, performing retroactive calculations, and costing/reporting. They provide a systematic way to encode contractual language as atomic, testable and auditable payroll logic.

The empirical evaluation showed a reduction of 91.1% in total payroll mistakes, a 95.2% reduction in the time taken to process retroactive payroll, a compliance accuracy rate between 97.2% and 99.4% across six multi-jurisdictional overlaps and a 85.7% reduction in the time taken to close audit queries. The cross-platform mapping showed that the architectural styles of Oracle Fusion Cloud HCM, SAP SuccessFactors, Ceridian Dayforce, ADP Workforce Now, and Workday Payroll were similar.

Governance controls (rule versioning, test coverage, parallel payroll run and clause-to-paycheck traceability) provide additional independent assurance of Finance, Internal Audit, labour relations specialists and employee representatives through the life cycle of the CBA. Work should continue to extend to emerging collective labour agreements, international works council architectures and integration with Artificial Intelligence contract analysis tools (Kubam 2024) to partially automate the transformation of clauses to rules.

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