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Blockchain-driven transparency in construction tenders: smart contracts and sustainable waste management

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Abstract

The integration of blockchain and smart contracts in the construction industry has the potential to revolutionize the tender phase and enhance waste management practices. The prototype is designed to enhance transparency, efficiency, and trustworthiness in Italian public procurement. To analyze the national public procurement database with a view to identifying common issues, which are often related to the lack of trust among stakeholders, Large Language Models (LLMs) are exploited. Blockchain technology has the potential to facilitate this process by eliminating discrepancies and disputes, providing a decentralized, immutable ledger to notarize data related to digital models submitted during the tender phase, thereby ensuring transparency and tamper-proof data. The automation of bid evaluations based on predefined criteria such as those pertaining to waste management, is a key feature of smart contracts, which are of particular importance in the context of construction sustainability. Such assessments are enabled, allowing for unbiased and transparent evaluations based on quantifiable data, with the results recorded automatically on the blockchain. This results in a more efficient tender process and the promotion of sustainable practices, as projects with superior waste management are given priority. A tailor-made blockchain protocol is put forth to delineate requirements and facilitate data exchanges. It establishes standards and procedures for data submission, verification, and evaluation, ensuring secure and transparent interactions and enhancing stakeholder confidence in a fair and transparent evaluation process. In summary, the use of blockchain and smart contracts in the construction tender phase improves data integrity, transparency, and efficiency. The focus on waste management indicators allows for objective project evaluations and the promotion of sustainable practices. This

innovative approach has the potential to transform public procurement, establishing a new global standard for the construction industry.

1 Introduction

Some of the issues affecting the Construction Industry are particularly significant in Public Procurement. Despite the considerable impact of the European Union's (EU) single market on the region's gross domestic product (GDP) and expenditure, as well as the advent of digitalization and e-procurement platforms, there is still great room for improvement as can be seen from the latest single market scoreboard analysis based on 12 indicators of quality, transparency, speed and accountability indicators (European Commission, 2022) reveals significant room for improvement.. Indeed, the processes in question remain predominantly "paper-based" rather than data-driven, resulting in Information Management and tender evaluation that are characterized by low transparency, time-consuming and error-prone tasks. The necessary information is frequently located within a plethora of documents, which are often incomplete and inconsistent with one another or with the initial requests, thereby negatively impacting the quality of the project. Consequently, this sector is characterized by inefficiency and the high prevalence of corruption and fraud. The Organisation for Economic Co-operation and Development (OECD) estimates that corruption and mismanagement results in losses amounting between 10 and 30% of global economic activity, or approximately 400 billion to1.2 trillion euros per year (OECD, 2019). Italy exhibits considerable room for improvement in comparison to other EU countries. Its indicators are relatively low, with a decision-making speed of approximately 200 days, which falls below the efficiency threshold of 120 days. Additionally, there is a need to enhance transparency, facilitate the inclusion of small and medium-sized enterprises and improve data quality (European Commission, 2022; OECD, 2019). While current procurement procedures have been somewhat digitalized using platforms, there has not been an update to the implementing regulation that would enable the transition from a paper-based approach to a digital and data-driven one. This indicates that the process remains suboptimal in comparison to the potential currently offered by digital technology and information models. The sole automated task pertains to the mere control of the existence of the requested documents (Meschini et al., 2023), as opposed to the verification of bids' content and their consistency and completeness with respect to the requests of the Public Client. A significant advancement is necessary to effectively and comprehensively digitize the process, enabling the utilization of information models and digitalized data, through algorithms that can automatically assess the content of the bidding models and related information (Pattini et al., 2022). This would enhance the process's efficiency, productivity, transparency and accuracy, reducing the likelihood of errors or the presence of incomplete or inconsistent bids.

2 Background

2.1 Public Procurement and Construction industry

It was demonstrated that an improvement in PP productivity, even by a mere 1%, could result in savings of 43 billion per year in OECD countries (OECD, 2019). Indeed, it could have a high return on investment as Public Clients are significant purchasers and can lead through efficient processes with improved sustainability (Pellegrini et al., 2021). It is also crucial to achieve the objectives set out in the Agenda 2030, as promoted by the NRPP, which has identified digitalization, sustainability and ecological transition as its core principles, with the majority of its resources allocated to these areas. Consequently, EU directives and Italian regulations strongly encourage the utilization of digital and data-driven methodologies to augment the efficiency of the public procurement sector, alongside the implementation of green public procurement, which continues to encounter challenges in the context of prevailing paper-based procedures (Lavagna et al., 2019; OAV, 2022; Sapir et al., 2022). The application of the most economically advantageous tender criterion (MEAT)is necessary to allow for the incorporation of qualitative and quantitative criteria for the purchase of goods and services at an optimal life-cycle cost and quality.

This entails numerous variables that must be considered, particularly in the context of environmental verification. The current approach, in which a judging committee of experts is solely responsible for evaluation, lacks the use of digital tools or automation, which hinders an objective assessment and frequently results in outcomes that do not fully align with the expectations of customers. The implementation of data-driven and digital methods would facilitate the streamlining of procedures and processes for verifying compliance with client and regulatory IRs. This would allow for improved judgment on bids, which are currently entrusted entirely to a jury and fifteen subject to arbitrariness. The use of data-driven and blockchain methods can make the process more objective and transparent, while also facilitating the verification of sustainability protocols that are currently experiencing significant challenges in practice. The application of GPP is particularly limited in this regard (Lavagna et al.,2019; Meschini et al., 2023; Pellegrini et al., 2021) (Figure 1). Consequently, the complete digitalization of this phase would undoubtedly result in a notable reduction in decision-making times, largely due to the automation of numerous procedures, while simultaneously lowering costs. The digitalization of process management has recently been identified as a potential turning point for the sector. Furthermore, the European Union has proposed a common public procurement strategy, comprising six measures, with the aim of improving the sector through collaborative approaches between public administrations and stakeholders. These strategies encompass the advancement of digitalization, enabling data-driven decision-making, and the incorporation of digital methodologies throughout the entirety of the procurement process. This approach is designed to facilitate the implementation of fully digitalized processes, thereby realizing substantial time and cost saving. Additionally, it aims to enhance operational transparency and mitigate disputes (European Commision, 2017).

Perf. Ind.	AT	BE	BG	CY	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IS	IT	LI	LT	LU	LV	MT	NL	NO	PL	PT	RO	SE	SI	SK
Indicator 1	29	24	34	16	42	25	23	32	48	28	14	22	23	33	21	14	37	18	34	23	37	15	19	16	52	24	42	13	51	30
Indicator 2	7	2	23	39	10	6	5	11	1	10	3	2	5	5	1	3	5	7	6	6	8	9	9	1	9	5	23	1	11	5
Indicator 3	4.8	3.7	5.8	3.8	5.7	2.1	6.5	9.2	3.3	4.3	7.0	8.4	7.9	9.4	3.3	n/a	6.0	n/a	6.2	4.5	10.9	4.4	3.8	n/a	7.9	2.4	8.7	6.8	4.7	6.1
Indicator 4	6	16	1	9	5	13	17	17	3	1	21	6	3	11	16	1	11	0	2	1	17	0	3	11	3	4	1	1	5	7
Indicator 5	30	37	87	94	81	66	50	80	85	22	58	8	1	49	15	90	40	73	93	70	72	92	21	25	58	65	86	83	68	96
Indicator 6	87	110	100	128	90	51	70	52	242	157	88	92	90	112	108	53	197	43	68	110	72	177	84	49	60	99	105	44	82	175
Indicator 7	57	33	74	88	68	61	52	82	51	48	56	41	50	75	67	92	48	94	91	63	92	92	67	46	55	45	53	58	85	82
Indicator 8	78	59	72	85	95	71	62	90	85	58	60	66	39	74	74	99	60	100	94	96	91	91	56	48	58	58	63	12	80	84
Indicator 9	11	31	35	22	19	18	25	30	37	30	28	42	38	38	14	6	27	9	42	8	36	16	16	10	46	35	47	6	40	33
Indicator 10	4	2	2	0	1	1	1	0	0	4	0	2	0	0	3	0	1	0	0	0	0	2	1	0	1	3	0	2	7	0
Indicator 11	51	90	0	0	6	99	43	5	88	29	6	88	0	12	33	25	94	80	5	98	4	3	43	47	66	58	0	4	2	1
Indicator 12	87	14	0	1	2	97	13	0	76	10	0	54	0	0	69	7	85	96	0	92	0	18	6	0	48	27	1	1	1	0

Figure 1. Scoreboard of EU Single Market – Public Procurement, 2022

2.2 Public Procurement database scraping with LLM

The creation of new tenders frequently necessitates an examination of previously published tenders within the specified target area. The objective of this research is to propose the adoption of Retrieval-Augmented Generation (RAG), which is a Natural Language Processing (NLP) approach that combines information retrieval (IR) techniques with LLM text generation. This enables the production of more accurate and relevant responses to user queries (Guu et al., 2020). The paper demonstrates the information flow required to construct a recommendation system based on the national Anticorruption Authority (ANAC) database, which contains the "metadata" of the Italian Public Administration (PA) tenders since 2010. Each text, comprising a few paragraphs describing each contract, is transformed into a numerical vector using Large Language Models (LLMs) provided by Cohere and OpenAI. The resulting embeddings are stored in an internal database (vector base) and are available for rapid retrieval when a content search is submitted by the user. In response to user queries, the system returns the k most similar procurement examples, determined by the strength of the embedding between the query and the vectors in the vector base. To assess the efficacy of the recommendation system, a metric known as NDCG (Normalized Discounted Cumulative Gain) is employed. This metric gauge the relevance and usefulness of the items presented in response to user queries. The measure is normalized against an ideal ordering of the items in the answers (Figure 2).

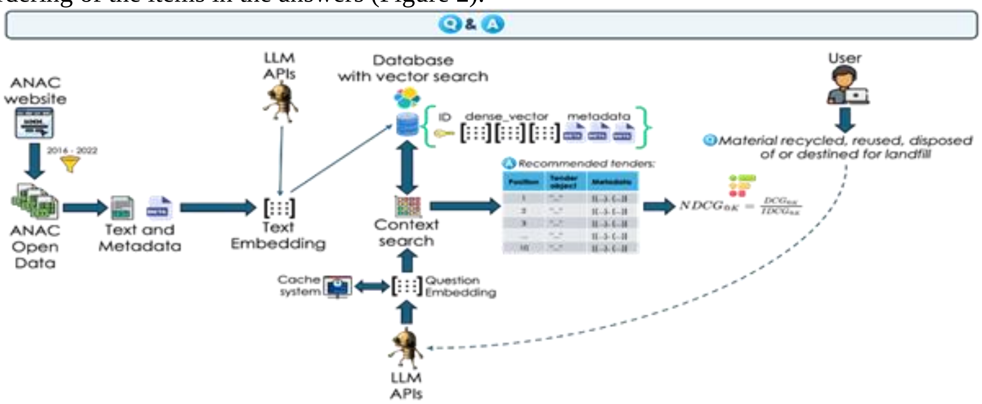

Figure 2. Database scraping workflow on the ANAC website for waste management

Although the BM25 model (Robertson et al., 2009) has a strong historical performance, it is evident that it has limitations when used as a baseline in this comparison. The results demonstrate that more sophisticated and expansive models tend to exhibit superior relevance ranking performance, although the extent of improvement may vary depending on the query and LLMs utilized. This indicates that the selection of a model for information retrieval tasks should consider the trade-offs between computational resources and the incremental gains in retrieval effectiveness (Nai et al., 2024).

Accordingly, the subsequent phases of the research will focus on:

1. Implementation of a service using Flask and ReactJS that will facilitate web-based tool usage.
2. Introduction of further evaluation metrics in addition to the NDCG and a deeper exploration of qualitative evaluation by domain experts, with the addition of more queries to be submitted to the system.
3. Comparison of the proposed RAG framework with other existing frameworks, such as Fast-RAG.
4. Utilization of open LLMs such as LLaMA in lieu of proprietary tools, including Cohere and OpenAI.

2.3 Automatic checking, evaluation and awarding in construction tenders

Among recent technologies, blockchain and Smart Contract have demonstrated considerable potential to enhance the traditional contract execution process. They facilitate a robust connection between stakeholders, materials and processes, and enable the use of computational language in contractual clauses, which prevents free interpretation or information asymmetry. This is evidenced by sector research (Kim et al., 2024; Pattini et al., 2022; Sreckovic et al., 2022). During the tendering phase, bidders are expected to develop their projects in accordance with the specifications set forth by the client and the relevant regulatory requirements. Smart Contracts can be drafted as a ledger that records all information exchanges among the parties, thereby ensuring high transparency and reliability. This is crucial for providing collaborative approaches and trustworthiness. A blockchain platform allows for the exploitation of a full digital process, enabling the faithful development of bidding models starting from either the preliminary or final BIM model, in accordance with the guidelines set forth in the notice documentation. The terms of the contract, the criteria for evaluating bids, and the notice documents can be translated into a Smart Contract, which will then be unchangeable and shared equally among all participants. Once submitted, the bids can be stored on the platform in an immutable state, thereby ensuring a transparent and auditable awarding process. The bidding models can be automatically evaluated by comparing them against the Information Requirements (IRs) and evaluation criteria defined in the notarized tender documentation. The findings of each bid verification can be compared and validated by executing the predefined Smart Contract. Once the procedure has been concluded, the scores assigned to each bid can be automatically compared, identifying the bid that has achieved the highest level of compliance with the specified requirements. The blockchain provides a distributed digital environment that can eliminate the issues of information asymmetry, ensuring information trust and transparency throughout the process (Kim et al., 2024; Pattini et al., 2022; Sreckovic et al., 2022). It is not necessary for the parties involved to establish trust in one another; they can instead rely on the system itself. As a result, it is possible to provide superior project quality, transparency and objectivity, preventing clashes or obscurity in the process with potential disputes, additional expenses and time delays (Figure 3).

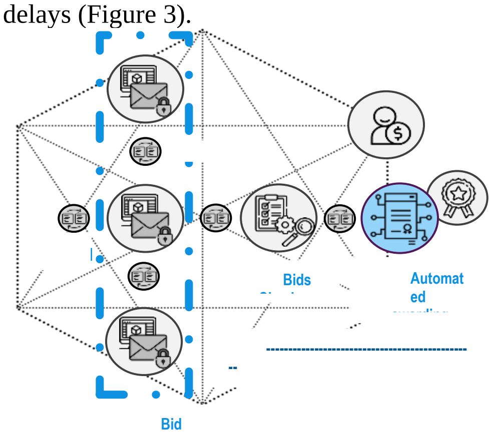

Figure 3. Automated tender process scheme

Aiming at achieving this objective, current approaches need to be revised from a model-based, open-source perspective, thereby enabling the full digitalization and data-driven approaches to tender evaluation. Such a shift could prove highly disruptive, necessitating a fundamental change in perspective (Meschini et al., 2023). The fundamental concept is that the system operates on a web platform that incorporates data, IFC (Industry Foundation Class) models and processes that have been formalized in BPMN 2.0 (Business Process Management Notation), thus making them machine readable (Object Management Group, 2011). The client disseminates the tender documentation via the platform, whereupon the bidder downloads it and the final IFC model. Subsequently, the bidder produces a bid and uploads the IFC bid model. A unique identifier, such as a hash, can be assigned to each bid and subsequently verified against the Client's and regulatory IRs. Models that fail to meet the requisite standards may be disqualified, with the rationale for this decision noted. Those that satisfy the requisite standards may then proceed to the evaluation phase. Subsequently, the judging commission initiates the evaluation process, which is conducted in accordance with the MEAT criterion. This process can be automated, thereby increasing the objectivity and transparency of the evaluation.

Subject	Features
Evaluator	Web platform with Judging Commission partial actions
Tools	Excel sheets, digital micro services, business intelligence, blockchain (Software, digital tools, simulation engines, codes, rule sets)
Formats	Open and machine readable (IFC, json, csv, xml, RDF, …)
Evaluation references	Machine-readable rule sets, tender specification and regulations
Awarding criteria Weighting	Objective – notarized - transparent
Performance evaluation	Systematic, simultaneous and automated
Tender duration	Strongly reduced-few days

Table 1. Tendering process features

The use of open formats, evaluation algorithms and score visualization and comparison through analytical dashboards allows for the evaluation of both the individual bid and the overall comparison, up to the award. Furthermore, the winning project model is stored on the platform. By leveraging blockchain and smart contracts, its consistency is guaranteed, as it becomes unreviewable and can be utilized as a benchmark for the subsequent construction phase. This provides a valid prototype of the building, developed with an information modelling and management approach and then structures the information according to the client's requirements and needs, ensuring consistency and integrity (Kim and Kim, 2024; Meschini et al., 2023) (Figure 4).

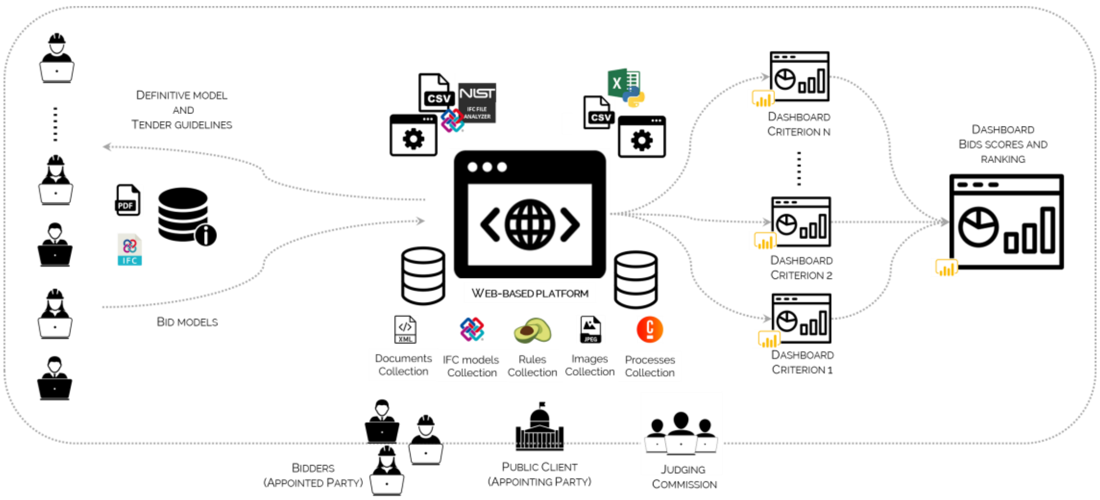

Figure 4. Model-based, open-source, semi-automated approach for bids evaluation and tender awarding

3 Methodology

3.1 Automating bids' evaluation

A replicable methodology was devised to automate bid evaluation by extracting data from BIM models, involving four key steps:

1. BPMN Normalisation: The procurement and criteria evaluation processes are structured using BPMN, allowing identification of information exchanges and automatable tasks.
2. Information Requirements (IRs) Definition: IRs mapping in IFC via standard or customised property sets.
3. Data Conversion and Evaluation: IFC models are converted into CSV sheets using the NIST IFC Analyzer tool, enabling the extraction of required quantities and scoring via an evaluation algorithm.
4. Analytic Dashboards Development: Dashboards are created to visualise and compare bids against individual criteria, sub-criteria, and overall scores.

Notably, the NIST tool enables viewing all entities and attributes simultaneously, generating spreadsheets from IFC files (Meschini et al., 2023). The procurement process is formalised in BPMN 2.0 to ensure a machine-readable, digitalised system linked to data-driven approaches and smart contracts.

The BPMN diagram includes four lanes: the web platform facilitating the exchange of information; the two upper lanes representing the Public Client and the Judging Committee; and the lower lane representing the Bidders. These actors exchange information, which can be notarised through the blockchain interface. The Public Client initiate the process by uploading the tender documents to the platform, including the IRs, accompanying documents, preliminary or definitive models, and the awarding criteria with their weights. Additionally, the bidding models can be notarized ensuring data immutability and sharing for maximum transparency.

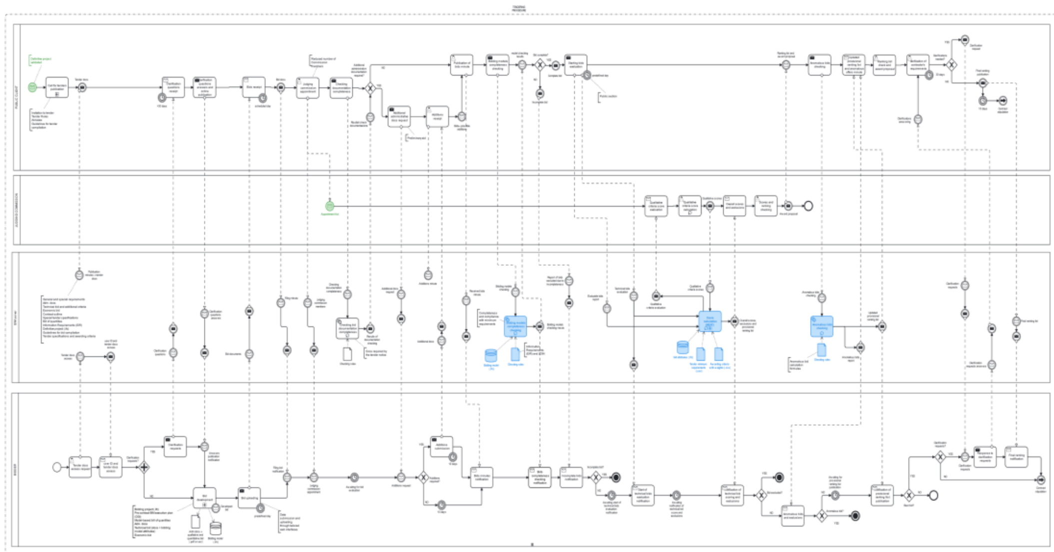

Figure 5. BPMN of the procurement process with automatable sub-processes highlighted

The verification of models can be automated to assess compliance with acceptance thresholds for each criterion and anomaly thresholds, enabling the automatic acceptance or exclusion of bidding models. A smart contract should record the verification results and link to the contract for bid evaluation against awarding criteria. This contract is activated if bidding parameters meet or exceed the minimum acceptance thresholds and do not fall within anomaly ranges. Once the best bid is determined, the smart contract for awarding the tender is triggered, with notarisation of the awarded model. This model can subsequently be used to monitor progress during the construction phase.

1. The impacts which can be envisioned include:
2. Enhancing transparency and fostering collaboration among stakeholders.
3. Reducing appointment delivery times through automated design validation.
4. Ensuring automated and precise verification of compliance with information requirements.
5. Supporting Green Public Procurement (GPP) through data-driven automation, aiding the Client in adopting circular economy principles, and improving waste management by optimising waste production.

Guaranteeing rewards for stakeholders (via automated payment releases and token delivery), increasing objectivity and shortening decision times.

3.2 Potential of Smart Contract in construction industry

Smart contracts are self-executing agreements where the terms are directly encoded into the contract. They automatically enforce and execute the terms once predefined conditions are met, removing the need for intermediaries. This automation and transparency are particularly advantageous in the construction industry, where projects involve numerous parties and complex agreements (Pattini et al., 2022; Sreckovic et al., 2022; Kim et al., 2024). Implementing smart contracts in construction offers several benefits, including automating contract execution, which speeds up processes and reduces human error; recording every transaction on the blockchain, visible to all involved parties; significantly reducing administrative costs and delays by eliminating intermediaries; and ensuring the immutability of contract terms and project details, preventing tampering.

The main impacts are related to:

1. Efficiency: Eliminates manual paperwork and reduces administrative overhead.
2. Security: Immutable records prevent fraud.
3. Trust: Transparent execution builds trust among stakeholders.

The process of defining a smart contract begins with identifying specific objectives and requirements, followed by gathering all necessary conditions and goals. The appropriate blockchain platform must then be selected, such as Ethereum or Hyperledger, based on scalability, security, and transaction costs. The development phase involves writing the smart contract code using languages like Solidity, ensuring it accurately reflects the agreed-upon conditions and actions. Rigorous testing is conducted in a controlled environment to ensure reliability and security. Once the contract passes all tests, it is deployed to the main blockchain network, making it accessible to all relevant parties. Continuous monitoring is crucial post-deployment to address any issues and implement updates.

Since the most critical part of designing and deploying a smart contract is the business logic, this can be automated using generative AI (Artificial Intelligence) (Petrovic et al., 2023). Generative AI, such as GPT-4, can create content based on input data, enabling the automation of smart contract drafting. This significantly reduces the time and effort required. By following predefined rules and conditions, AI ensures high accuracy and minimises errors, making the generated contracts ready for deployment. The workflow integration is straightforward: first, detailed requirements are gathered and fed into the AI to draft an initial contract. This draft is then reviewed by legal and technical experts to ensure compliance and accuracy. After thorough review, the contract undergoes rigorous testing in a controlled environment before deployment to the blockchain. Using generative AI for smart contracts offers several advantages, such as reducing legal and development costs, ensuring consistency across contracts, and speeding up the development cycle (Petrovic et al., 2023; Nguyen et al., 2024). However, it is essential to use high-quality input data, ensure regulatory compliance, and maintain human oversight to validate the AI-generated content.

4 Results

4.1 PoC: sustainable waste management in a construction tender

As previously mentioned, several challenges typical of the construction industry are particularly evident in public procurement and the tendering phase. In response, the EU has been promoting digitisation and the adoption of data-driven processes to enhance productivity, delivering high returns on investment and positive spillovers across the supply chain while reducing errors, omissions, and variances. Since the introduction of Directive 2014/24, significant emphasis has been placed on Green Public Procurement (GPP), recognising that the construction industry is one of the most impactful globally, accounting for approximately 36% of waste and necessitating a shift to circular economy models. Directive 2018/851 further underscored the importance of tracking and reducing construction and demolition waste through prevention, reuse, and recycling throughout the lifecycle.

In Italy, Legislative Decree 50/2016 marked a turning point by introducing GPP methodologies in public procurement and the MEAT (Most Economically Advantageous Tender) awarding criterion, recently extended to include BIM and IFC standards. However, challenges remain, particularly the low adoption of GPP and CAM (Minimum Environmental Criteria), largely due to the absence of simple, data-driven tools for tender evaluation with MEAT (Lavagna et al., 2019; Sapir et al., 2022; OAV, 2022). This reliance on paper-based procedures has prolonged procurement processes and affected the quality of awarded bids, wasting resources and limiting control over project performance and compliance with the client's Information Requirements (IRs).

A digital, automated method could address these issues by linking processes and data models through a web-based platform with blockchain notarisation, ensuring automation and trustworthiness. The proposed methodology was tested in a Design and Build procurement model, suitable for model-based approaches where building geometry is defined, and tenders are evaluated based on improving proposals. It focused on the semi-automated evaluation of waste management criteria—typically difficult to assess due to the vast data required. Incorporating these criteria from the tendering phase promotes GPP adoption and reduces environmental impact.

This approach could be extended to other CAM criteria and entire tender evaluations (Meschini et al., 2023). The case study involved a new school in Melzo, near Milan, using a Design and Build model with the MEAT approach. Although GPP and CAM were not mandatory, similar criteria were piloted to demonstrate how Information Modelling and Management can support and enhance the MEAT criterion's application (Figure 6).

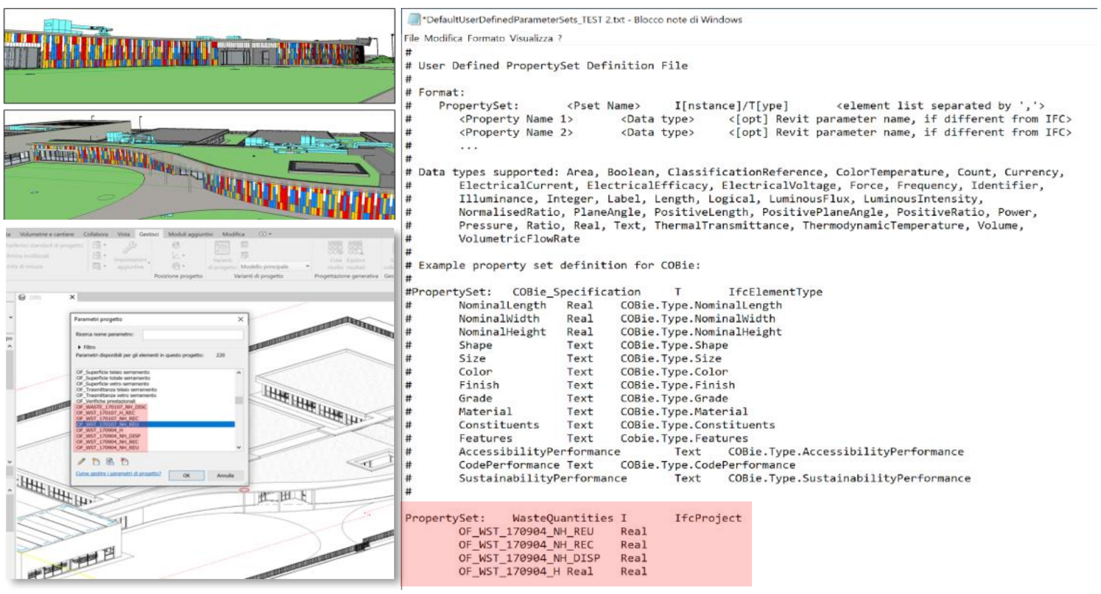

Figure 6. BIM model of the case study with parameters mapped in IFC

The criterion C 2.3, pertaining to the construction phase, necessitates the development and implementation of a waste management plan aimed at maximising the quantities of reused and recycled waste (Pellegrini et al., 2021). In line with the previously outlined methodology, related Information Requirements (IRs) were defined and exported using the open IFC format, incorporating a customised property set. This property set included, for each material identified by its corresponding European Waste Code (EWC), the four required percentages of waste quantities: reused, recycled, landfilled hazardous, and landfilled non-hazardous. To ensure maximum flexibility and customisation, the "DefaultUserDefinedParameterSets" feature was utilised. This process requires a .txt file containing a tailored script to define the property set named "Waste Quantities".

4.2 Smart contract and blockchain for the PoC

A smart contract was established to execute and store data on the blockchain, involving the previously identified stakeholders: the Public Client (Authority/PA), the Bidders, and the Judging Committee of experts. All participants are registered and verified through the smart contract, incorporating Know Your Customer (KYC) and Anti-Money Laundering (AML) protocols, as instructed by the client, regulators, and other relevant authorities.

Stakeholders interact with the system by sending transactions to the blockchain, making payments, transmitting data, and invoking the smart contract's functionalities. The process is divided into three phases, each with specified deadlines:

1. Privacy-preserving committal bidding
2. Validation

Automated determination of the winner and awarding.

(1) Privacy preserving committal bidding

The code of the smart contract that rules the bidding is shown in Figure 7 with some constraints checked and imposed about the bidder/project/min deposit/bidding phase being currently open, in red.

```
bidProject(3029-ID, 0x59F...3, 0x15A..0, 1000usd) payable
```

```
function bidProject(uint _ID, string memory document) public payable
                                                  checkIfProjectAssigned(_ID)  {

    // checks to be performed
    require(bidderMap[msg.sender] == true, "Not allowed bidder");
    require(_ID < projectsList.length, "No ID found");
    require(msg.value >= projectsCreated[_ID].min_deposit, "Not reached the minimum
    require(projectsCreated[_ID].bids_phase_open,
                                       "Proposing not open for this project");
    require(block.timestamp <= projectsCreated[_ID].next_step_deadline,
                                           "You are too late");

    // insert Bid in the Bid list of the project
    projectsBids[_ID].push(Bid({
            bidder: msg.sender,
            amount_deposit: msg.value,
            bid_document: document,
             amount_withdrawn_back: false}));
```

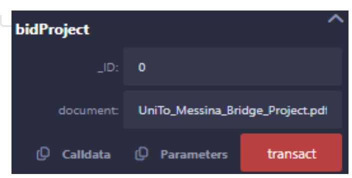

Figure 7. Description of the protocol and interface associated with the committal deposit for bidders

(2) Validation

Figure 8 shows a bidder sending an offer consisting of documents, quotes, and a deposit, then the bids are encrypted (hashed) to preserve the privacy and only the bidder will be able to reveal them later.

```
revealBid(2029-ID, "Thermal_TRX 175; Density 85; ...", BuildingDetails.bmi)
```

```
function vote_project_bids(uint _ID, uint _bid, uint _beauty,
                            uint _smart, uint _materials, string memory _comment)
                             onlyExpert
    require(expertMap[msg.sender], "Not an expert");
    require(_beautiful <= 5 && _smart <= 5 && _materials <= 5,
            "Vote not correct");
    require(projectsCreated[_ID].voting_phase_open == true,
            "Not voting phase yet"); //check if it is right moment to vote
    require(has_voted == false,
            "Expert already voted"); // check if expert has voted yet

    //add vote
    expertsVote: Votes({
        beautiful: _beautiful, smart: _smart, materials: _materials, comment: _comme
       })

    emit bidVoted(_ID, _bid);
```

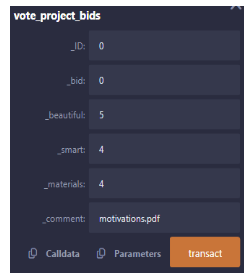

Figure 8. Description of the protocol and interface associated with the validation of experts evaluation

The deposit is binding, serving as evidence of the bidder's genuine interest (skin in the game) and discouraging undesirable behaviours, such as refusing to disclose unfavourable bids or submitting multiple bids to maximise chances and advantages (various strategies could be employed). Data are stored off-chain, as on-chain storage is costly, with an immutable link to the smart contract typically provided via IPFS. Various levels of privacy and accessibility can be configured.

The bidding phase concludes either at a predefined deadline or through an action by the client. The prototype includes an interface for voting experts and the smart contract code governing the experts' votes (Figure 9). It ensures that only recognised experts can interact with the contract, verifying their credentials. Additionally, it confirms the correctness of the vote format, the voting phase, and that each expert casts only one vote. Once a vote is submitted, it is recorded, and an event is emitted, visible to all stakeholders outside the blockchain.

When a bidder reveals their previously private and immutable bid, the smart contract ensures its consistency with the encrypted commitment made earlier, maintaining trust and transparency.

(3) Awarding notarization

The smart contract code uses the "quantified" bids for a deterministic and verifiable determination of the best bid, and the winner is awarded. Their cryptographic address (i.e. the proxy for their validated identity in the blockchain world) has been identified. In this phase, no bidder can propose new tenders and all bidders are incentivized to reveal their so-far private bids, no one can know or alter them, nor bidders can retract them. As soon as they reveal the bid, the contract pays them back the deposit and the experts can evaluate them, assigning a numerical score.

```
//calculate the best bid
for (uint i = 0; i < projectsBids[_ID].length; i++) {
    uint totalSum = 0;
    Vote[] storage votes = project_bids_votes[_ID][i];
    for (uint j = 0; j < votes.length; j++) {
        totalSum += votes[j].expertsVote.beautiful;
        totalSum += votes[j].expertsVote.smart;
        totalSum += votes[j].expertsVote.materials;
    }
    if (totalSum > highestVoted) {
        highestVoted = totalSum;
        Winner = projectsBids[_ID][i].bidder;
    }
}
// winner found
projectAssignment[_ID] = Winner;
projectsCreated[_ID].project_address_winner = Winner;
projectsCreated[_ID].project_assigned = true;

emit projectAssignedWinner(_ID, Winner);

return("Address of the winner: ", Winner);
```

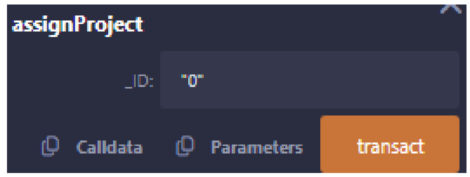

Figure 9. Description of the protocol and interface associated with the bidders' committal deposit

The justification for experts' scores can be recorded through a voting mechanism, or alternatively, an expert reputation framework could be established. A commit/reveal system, backed by a deposit, encourages proper behaviour from bidders, and appropriate strategies can be implemented to mitigate bias and arbitrariness in the evaluation of qualitative parameters (Figure 9).

5 Conclusion and further development

This research proposes a methodology that integrates digital technologies to achieve comprehensive digitalisation and introduces automated processes to streamline traditionally manual and subjective tasks. By avoiding time-consuming and unreliable methods, the approach enhances transparency, reliability, and objectivity. Improved production, review, and validation of information through optimised information management ensure higher compliance with Client and regulatory Information Requirements (IRs). This reduces errors, omissions, reworking, and associated costs, while also mitigating risks of corruption. The methodology enables straightforward and rapid verification of CAM or other environmental protocol applications, facilitating the adoption of Green Public Procurement (GPP) and lowering the overall project impact.

Blockchain and smart contracts contribute significantly by enabling secure tracking of information transactions, ensuring reliability and confidentiality. They also allow for the automated verification, evaluation, and awarding of bids according to compliance standards defined by the client. This automation extends to payment processes, improving the efficiency of Public Procurement (PP). Furthermore, the need for a central trusted authority or intermediaries is eliminated, reducing opportunities for corruption. Key Performance Indicators (KPIs), such as bids' consistency and compliance, will be introduced to measure improvements in transparency, efficiency, and sustainability in the tendering process, further enhancing accountability and outcomes.

Nevertheless, the proposed methodology faces several challenges. These include defining IRs and IFC Property Sets for evaluation criteria and contract terms, which requires managing large datasets and normalising procedures in a machine-readable format. Transitioning to a distributed, process-driven approach with full transparency among stakeholders also poses challenges, particularly given the sector's close-knit nature and concerns over privacy. Additional obstacles involve automating smart contract generation with high reliability and addressing the lack of IT skills within Public Clients and the construction industry. The absence of updated regulations and standards further complicates adoption.

Another critical consideration is mitigating the environmental and energy impacts of blockchain technology. This may involve leveraging Sustainable High-Performance Computing (HPC) centres, such as the one under study at the University of Turin. These centres would utilise renewable energy sources, such as solar power, and implement heat reuse systems to minimise carbon footprints.

Future research will focus on addressing these challenges to advance the adoption of sustainable, efficient, and transparent digital solutions within Public Procurement and construction industry.

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