Leveraging Digital Twins to Enhance Green Public Procurement in AECO Industry

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Abstract

The digital transition of process management and Digital Twins (DTs) are promising to bridge the gap towards Product Lifecycle Management (PLM) and revolutionize decision-making processes in AECO (Architectural, Engineering, Construction and Operation) industry. Public procurement particularly suffers of poor digitalization with ineffective processes and low adoption of Green Public Procurement (GPP) mainly due to the lack of digital and automated data-driven tools for tender evaluation. Leveraging DTs as virtual Prototypes (DTPs) could help to overcome the current discrete project performances evaluation and enable a systemic one, exploitable for bids evaluation besides performance and sustainability optimization.

The research adopts a PLM view to define a methodology aimed at developing DTPs starting from the bidding BIM models. The main objective is to integrate several DTPs and an Artificial Intelligence (AI) system in the aim automatizing MEAT (Most Economic Advantageous Tender) procedure and promote GPP adoption, providing an optimal and more objective data-driven awarding system and criteria weighting. Three crucial objectives should be accomplished: (i) the definition of a replicable methodology to develop the DTPs, (ii) the definition of their informative structure and (iii) the re-engineering of tender processes to bring full digitalization and automation. This could enable more effective decisions and performance optimization, bids objective evaluation, tendering procedure streamlining, transparency and sustainability enhancement. The awarded DTP, as a truthful "As-built" developed accordingly to defined information guidelines, must be exploited as the basis for valuable DTIs to manage the whole lifecycle, optimizing DTs development costs together with operational and maintenance costs.

Keywords

Digital Twin Prototype, Green Public Procurement, Tender evaluation, PLM, Waste Management

1. Introduction

Architectural, Engineering, Construction and Operation (AECO) industry notoriously suffers of low digitalization and productivity compared to other industry sectors. It still performs bad with limited performances ascribable to the huge fragmentation as well as the intrinsic complexity of construction projects with strong risk aversion discouraging new technologies uptake [1]. Such criticalities are particularly significant in public procurement which is usually underestimated with respect to other phases of the lifecycle as it has not an immediate impact, but it could have on the long-term, especially on sustainability and use of environmental, material and economic resources [2]. The low adoption of Green Public Procurement (GPP) both at European and Italian level represents an important gap mainly

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due to the lack of simple, digital and automated data-driven tools for Most Economically Advantageous Tender (MEAT) approach. This furtherly complicates the still highly document-based and fragmented procedures, affecting both tender procurement duration and the awarded bid's quality leading to waste of time and resources.

Although BIM (Building Information Modelling) gave a boost in the last decades, neither collaborative approaches nor digitalization are still fully accomplished. Key factors lie in struggling information and process management due to the lack of actual interoperability and representation limits pointed out by IFC standard [3,4]. Current BIM-based approaches, prevent to link process and data models throughout the whole lifecycle without updates when the project state changes and to record data change history. The solution for a breakthrough was identified in the digital transition of process management [1] enabling tasks automation and efficiency improvements. At this aim it could be useful a well-known approach in other engineering fields, namely PLM [5]. It supports a multidisciplinary and systematic performance view along the whole lifecycle, enabling to manage complex processes with a significant amount of data and strong variability. BIM was addressed as key for bridging the gap towards PLM, but it is not enough as it was introduced mostly to improve efficiency, enable collaboration, lower errors and omissions during the design and construction phases, with an intrinsic difficulty in feeding models with continuously updated and complete information through the lifecycle. Major limits lie in uncontextualized or missing process management information, in the static nature of BIM models data without a bidirectional and simultaneous relationship with the real world. Additionally, the synchronization of data updating is still a human task. Thus, many studies suggested to integrate BIM in a more complex perspective [6,7] with normalized processes stored together with data to enable data and process models linking and information contextualization.

A recent growing trend is promising to bridge the gap towards PLM and more sustainable choices in AECO industry, namely Digital Twins (DTs) [8]. Their interlinked and dynamic nature could be the solution for the management of complex systems such as those concerning construction projects, enabling an actual revolution in Information Management (IM) and decision-making processes. This especially with the aim of enhancing public procurement productivity and promoting GPP [9] adoption as required by EU directives and Italian Legislative Decree (L.D.) 50/2016.

Although a unique definition of DT in AECO industry has not yet been formulated, its first formalization was provided by Grieves in the field of PLM [10]. In this perspective, the DTs could be developed starting from the early design phase as DTPs, with the dual objective of optimizing project performance and structure the basis for the future DT Instances (DTIs) exploitable in the lifecycle. DTs market is expected to grow exponentially in the coming years with major part of buildings foreseen to have a virtual twin providing added value thanks to the easily information and process management through the lifecycle [11]. Thus, it is advisable to implement the DT starting from the early design phase, optimizing the use of resources, developing time and costs, in addition to operational and maintenance costs. This could help to over-come the current discrete project performances evaluation in favor of a systemic and full digitalized one, useful for bids assessment, performance, and sustainability optimization.

With the aim of encouraging GPP adoption, the research proposes an innovative and automated MEAT approach based on the integration of DTPs, normalized processes and an AI system through an open-source distributed platform based on Web of Linked Data principles. Leveraging DTPs during the tendering phase by aggregating them in a DTPs System exploited in a virtual ecosystem enables to evaluate different design proposals [10], optimizing decision-making and identifying the optimal solution. The key concept is that the DTPs must not be disposable but reusable as the basis for future DT Instances (DTIs) which will gather also dynamic data from field to manage the whole lifecycle. At this aim the DTPs should be developed starting from the BIM biddings models submitted accordingly to a defined IFC schema, exploiting Semantic Web and Linked Data principles [12,13] with easily accessible information stored in the open-source collaborative platform, also facilitating the DTPs enrichment throughout the lifecycle. The main goal is to provide an optimal and more objective data-driven awarding and criteria weighting system, in addition to a full digitalized and automated evaluation procedure, providing tendering procedure streamlining, transparency and sustainability enhancement.

The paper presents a methodology aimed at developing vertical DTPs (VDTPs) and then horizontally integrating them in a DTP system for the automated criteria evaluation in MEAT procurements. At this aim, three crucial objectives should be accomplished, that is: (i) the development

of a replicable methodology to develop the DTPs, (ii) the definition of their informative structure, related Information Requirements and how data should be gathered and (iii) the normalization and re-engineering of tender processes through BPMN 2.0 (Business Process Modelling Notation) [14] in a machine-readable way to bring full digitalization and automation.

Due to the numerous and complex domains integrated in a construction project, a scalable approach is adopted. With the aim of overcoming the lack of automated and user-friendly tools enabling sustainability criteria evaluation, the developed methodology will be tested starting from the evaluation of the mandatory yet not fully applied CAM (Minimum Environmental Criteria) [15]. A Sustainability DTP will be developed and firstly tested for the automated evaluation of waste quantities in two real Italian Design-Bid procedures [16]. Waste generation could be considered starting from the early designer phase and this is key to optimise quantities and reduce the environmental impact of the project. Assessed and validated in comparison with previous developed approaches, the methodology then will be extended to other CAM criteria and could be further extended providing the whole tender evaluation.

2. Background and motivation

2.1. A process-based open-source collaborative web platform

The research is conducted under the umbrella of an Italian Research of National Interest Project (PRIN) which promotes the digital transition of project management aiming at overcoming the afore illustrated limitations posed by current BIM-based collaborative approaches [17]. The goal is to integrate data and process models throughout the whole lifecycle in a collaborative process-based framework by jointly stored them through typed links with a customized semantic. Web of Linked Data technologies will be exploited [18]. In particular, the framework is based on the following technologies:

- Semantic Web to translate BIM models in graph format (i.e. RDF) through tailored ontologies;
- Linked Data to enrich BIM models with missing data by interlinking them from different domains through customized typed links;
- BPMN 2.0 to define and formalize data generating processes in a machine-readable way, enabling external actions (i.e. from humans or micro services) to be called [19].
- Blockchain at the top level aimed at the decentralized notarization of transactions and documents liability tracking [20].

Accordingly, the major outcome of the PRIN project consists in an open-source, distributed, collaborative platform to enhance cooperation in an easy-to-use digital environment. The involved research units should develop several Proof-of-Concept (PoC) use cases to demonstrate the easy collaboration and information exchange. The present research deals with the PoC use case for the design phase with the goal to exhibit how checking procedures could be developed and automated throughout the Web of Linked Data platform and how links between design data, processes and system performances can be formalized, depending on the evaluated criterion. A key concept to maintain information requirements consistency through the design phase and the whole lifecycle, avoiding shifting away from the original intent, especially in competitive biddings. Linked Data and Semantic Web combined with IFC through the Web of Linked Data platform provide a highly scalable and customizable approach for the DTs definition. IFC models could be translated in graph format with missing parameters to generate DTPs linked through tailored typed links. Such DTPs can be initially fed by bidders input and then incrementally enriched as the lifecycle of the building progresses.

2.2. Digital Twins: the bridge towards PLM

NASA provided the first formal definition of a DT, but the general concept was firstly provided by [10] in PLM by defining the fundamental elements of a twin model: the real part, the digital part and the information links between them [21]. Grieves identified three types of DTs with a growing level of maturity and they are conceived as dynamic and evolving models throughout the lifecycle. Firstly, the DT emerges virtually with the DTP and then takes physical form during the production phase and the operational phase as DTI, until the disposal. It should be noticed that at the early stage the physical

system does not exist yet and the DTP takes place in a virtual space identifiable with the digital space of information models. Before the advent of computer design, the system had to be costly implemented in a physical prototype. Now, very complex systems and shapes can be easily modelled with no need of a physical mock-up and the DTP could be exploited to predict future behaviour and performance of the product (i.e. building) in order to check when it represents the optimal solution and meets the proposed requirements [11]. DTs are gaining attention in AECO industry due to the increasing complexity of construction projects and the widespread integration of digital tools which provided a constant increase of data to be managed throughout the building lifecycle. So far, there is no commonly agreed definition of a DT in AECO industry, but almost all the attempts include the three key features aforementioned [20, 21]. Many studies agree that there might never be a universal definition of DT; rather its meaning depends on the developing purpose. Indeed, the great value provided by DTs lies in the ability to obtain the right information at the right moment. Thus, it should be tailormade based on its scope of replicating some behaviour of the physical asset avoiding replicating every part of the building. On the contrary, its bidirectional link with the virtual world is essential, enabling simultaneous data updating as soon as a change occurs. Some studies already made a parallelism with the DT types defined by Grieves, in particular [22] borrowed the DTP definition to the Building DTP: "*A Building Digital Twin describing the AECOO asset during its design and construction. It contains the informational sets necessary to describe and produce a physical version that duplicates or twins the virtual version.*" Accordingly, during the design and tendering phase, a Building DTP should be exploited in a virtual world evaluating different design proposals to identify the optimal one (i.e. the most advantageous bid). This could be disruptive as until now construction projects were a siloed set of project performances, evaluated through document-based approaches which prevented to estimate the impact that a change in input could have on the single and overall project performance. No prototype of the building with a holistic view of its performances was available and projects' comparison concerned just single parameters disjointed from their impact on installation and maintenance costs or resources consumption. A well-structured DTP can provide a complete and valuable prototype, allowing to evaluate the designed performances and choose the most sustainable solution also with respect to the expected savings. Nevertheless, although [10, 22] agree that the DTP *"…has to contain all the informational sets necessary to the future actual physical twin (DTI).*.", the DTP structure and information requirements related to the several performances to be evaluated is still undefined. As [23] points out, few research investigated the DT across the whole lifecycle, highlighting several gaps especially concerning the early design and disposal phases. This suggests that the actual benefit might have been missed yet and that the DT information requirements across the lifecycle should be investigated to provide valuable applications in a PLM perspective, in addition to useful information protocols for DTP development. An IM approach is strongly recommended as suggested by the IM Framework in the pioneering case of the National DT Britain [24].

2.3. Need for a green and digital transition of public procurement

The 14% of the European Gross Domestic Product is represented by Public Procurement and is regulated by EU directives with the aim to maximize value in the public sector and ensure compliance with three key principles: equal treatment, non-discrimination and transparency [27]. EU commission measured the performance of single markets in State Members to understand their public procurement efficiency [27] pointing out a bad performance for Italy with just two satisfactory indicators among 12 and the "Decision Speed" among the six not satisfied. [28] highlights an average starting time of a public procurement of 4 years and 5 months with the tendering phase averagely lasting between 5 and 20 months. The main cause of long "processing times" (i.e. the time between the end of one phase and the start of the subsequent one) lies in bureaucratic delays [25, 27]. Concurrently, both at international and European level, GPP is promoted to integrate requirements and criteria in order to achieve value for money in the whole lifecycle of a project and reach more sustainable practices. The 2014/24/EU Directive emphasizes the key role of Public Clients in realizing a smart, inclusive, and sustainable growth. Italy was pioneering with the innovative L.D. 50/2016 which introduced GPP as mandatory in public tenders through the MEAT approach. The most convenient bid must be identified by crossing price and quality, based on the lifecycle performance of a project. Nevertheless, GPP is still poorly

adopted mostly due to the lack of staff training and competences, generating issues in drafting sustainability criteria for tender documents. A worsen factor is the lack of digital and automated tools, preventing Public Clients to control project impacts in terms of both performance and sustainability. Furthermore, although the requirements of L.D. 50/2016 for the application BIM, project deliveries are still document-based struggling the whole bids documentation checking.

Therefore, digital, automated, and data-driven methods would be fundamental to enable easily project performance control and visualization promptly displaying the impact that some design choices might produce both at single and global performance level. It is key to provide administrators, judging commission and all the involved parties with actual awareness of their choices and sustainability impact. At this aim, a system of DTPs receiving offers in real-time through a web-based platform and enabling their timely evaluation and visualization at once would be essential albeit very complex:

3. Methodology theoretical overview and path description

Firstly, the methodology theoretical overview is provided to clarify research boundaries and objectives, then the replicable methodology path to leverage DTPs and AI through the Web of Linked Data platform and automatize MEAT in Design-Bid procurements is illustrated.

The principal axiom of the present research is that the developed prototypes must not be of the "disposable" type and intended just for the tender phase, rather it must be scalable and reusable to enable aware and optimized decisions concerning sustainability (e.g. costs, use of resources, compliance with environmental protocols, etc.) during the whole lifecycle. Thus, it must be framed as Grieves did in PLM and as [22] did in AECO industry. The research intends to provide a step forward with a DTP development methodology and detailed informative structure exploitable both as a mean for tender evaluation and as the basis for future DTIs. The DTPs born virtually in the tender phase as a tool exploitable in Design-Bid procurement to automatically evaluate the technical offers uploaded through a web-based platform. Therefore, their inputs are represented by the static project parameters extrapolated by a tailored IFC bidding model exploitable to develop all the DTPs needed in the bids evaluation and awarding. Another axiom concerns the fact that the proposed methodology is tailored with respect to Design-Bid procurements with a definitive project in which the Appointed Party realizes the final design and executes works.

It represents a valuable framework for the application of IM approaches [28, 16], especially with the aim of developing DTPs since the geometry of the project is defined and the bids are based just on performance improvement proposals. Moreover, defining a DTP exploitable as the basis for the DTI for the lifecycle management of a project with low import or less complex awarding criteria and a simple O&M phase, would be unproductive and antieconomic due to the huge effort required. For each criterion involved in the evaluation, VDTP will be developed, enabling the analysis of the single side performance. Then all the VDTPs related to an offer will be horizontally integrated in a Digital Twin Prototype system (Figure 1) useful to evaluate the single bid global performance and the impact on the overall. As it still lacks the definition of an informative structure for the DTP with related information requirements, the focus is not just the development of the DTPs, and the attention is centered on the set of processes and information concerning the creation and management of tailored DTPs.

It is not feasible to develop the whole DTP system enabling to simulate all the project performances at once, thus a bottom-up approach is adopted in order to define a replicable methodology useful to cover all the criteria/project performances. The methodology will be tested starting from CAM criteria evaluation and then extended. It starts form waste management criteria as part of a wider Sustainability DTP which will comprehend all CAM criteria. The research aims to exploit a previous work which dealt with Construction and Demolition Waste (CDW) minimization and selective demolition criteria and defined a replicable IM Modelling (IMM) approach to consider CAM criteria from the design to the call for tender phase [16]. The long-term objective is to extend the previous work in a more holistic approach by adding further CAM criteria evaluation such as building envelop performance in addition to lifecycle and disposal costs. In the short-term the previous case studies are exploited to test the validity of the methodology and the potentials of customized DTPs in enabling sustainability criteria automated evaluation with a holistic digitalized approach, improving GPP. Following the description of the main steps and tasks of the proposed methodology.

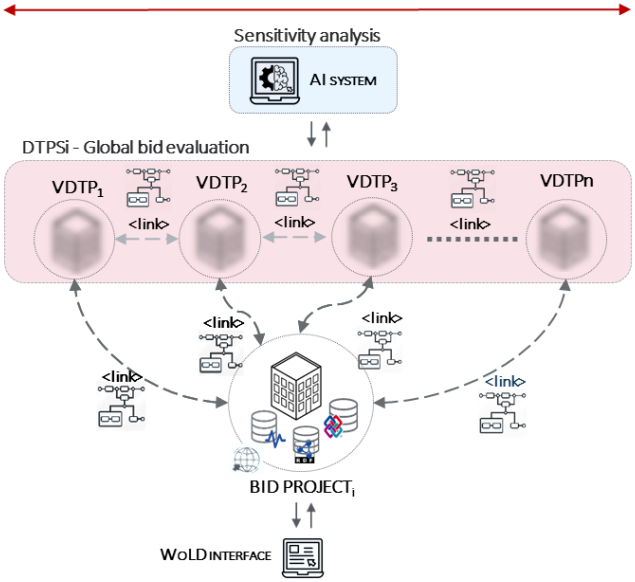

Figure 1: Digital Twin Prototypes horizontal integration in the DTPs System.

3.1. Tender processes normalization.

The first step concerns the formalization of all the processes and sub processes related to the offers evaluation, namely: (i) the global tender procedure, (ii) bid evaluation method, and (iii) evaluation of single performances considered. As stated before, BPMN 2.0 will be exploited, providing an intuitive graphical notation yet capable of representing complex semantics and machine-readable processes (i.e. xml format) able to call external interventions from humans or micro services. This normalization enables to identify both the information needed at a specific step of the process and by the related actor, that is the information requirements for each VDTP needed, and automatable tasks. Consequently, it is possible to check which input could be directly filled in the IFC bidding schema and which one should be linked through LD. The BPMN formalization allows also to define the needed outputs for single criteria and sub-criteria evaluation, in addition to the queries and rules to extrapolate needed information for VDTPs from the Web of Linked Data platform. Finally, the availability of machine-readable, normalized processes enables their optimization and automation through AI systems.

3.2. Vertical Digital Twins Prototypes and KPIs definition.

In this second step, VDTPs will be developed from the IFC models submitted by the participants and stored in graph format through the Web of Linked Data platform. Thanks to the previous BPMN formalization, the information requirements for each VDTP needed in the global evaluation are known and the models could be enriched accordingly to generate them. A key step is the definition of the queries to generate needed simulation models from the knowledge database and the KPIs (Key Performance Indicators) which could be monitored to promptly correct any deviations from expected targets. Ideally, for each bid should be developed as many VDTPs as the number of tender evaluation criteria, starting from each bidding IFC model developed basing on the given scheme and stored in graph format through the Web of Linked Data platform. The main outcome consists in a series of isolated VDTPs enabling single performance evaluation. It may seem onerous, but once needed VDTPs, related information requirements and extrapolation query are defined the process can be reiterated for each bid and machine learning could be exploited to automate this task.

3.3. Digital Twin Prototypes System implementation

Once the VDTPs are defined, they will be horizontally integrated to set-up the holistic evaluation of each bid's project performance (Figure 1). This step will involve the formalization of the

interconnections to set-up the DTPs system, enabling the definition of the links between the VDTP. A major outcome will be the simultaneous visualization of both global and single bids scores by means of tailored dashboards implemented through the Web of Linked Data platform. Thus, the user can be aware of the impact that a change in input has on the project performances, both at global and local level, in addition to costs and sustainability. A major outcome at this step will be the definition of the queries which enables to implement the DTPs system needed for the global bid evaluation (i.e. one DTPs system for each bid or tender project), based on defined information requirements.

3.4. AI system integration and global tender evaluation

A key step will concern the implementation of the most suitable AI system to provide the automation of MEAT approach, that basically is a multicriteria analysis [29, 30]. Furthermore, AI will enable the sensitivity analysis of the information requirements both of the single VDTP and of the overall system (i.e. DTPs system and tender evaluation). This enables deeply understand how a change in input impact on the single VDTP and on the overall, revealing hidden and direct links between various project's domains and enabling their formalization. As real cases are simulated, the AI system can be trained providing a growing knowledge of such links between the involved parameters in the tender evaluation. Then it will be possible to define and optimize a multicriteria scores aggregation system also considering the impact that a parameter change has both on the single performance and on the global one, in addition to that on sustainability and costs in a PLM perspective. In fact, increasing a single parameter performance doesn't ensure significant positive repercussions also on costs or global performance. Rather, it might lead to greatly increased installation and maintenance costs compared to slight savings. Exploiting AI and it could be provided a more objective, effective, and aware bids evaluation system.

3.5. Proof-of-Concept: Sustainability DTP for automated CAM criteria evaluation in Design-Bid procedures

The final step concerns the PoC development aiming at applying the proposed methodology to real case studies and analyse the benefits and criticalities of the innovative tender approach. As already stated in previous sections, the research aims to further promote the adoption of GPP in Design-Bid procedures and take a step forward respect a previous study [16] providing a holistic, automated tender evaluation and awarding. The methodological path and tools described in previous section are here contextualized and implemented through two Design-Bid Italian procurements for new school buildings. Aiming at CAM checking, the application of the proposed methodology starts from the automated evaluation of the waste quantities and disposal costs related to the "Final dismission" CAM criteria which will be part of a wider Sustainability DTP that in the future will consider other categories providing a multidisciplinary approach. Leveraging it from the tender phase will enable to optimise quantities and reduce the project environmental impact with a better resources allocation and optimisation by choosing materials with low waste quantities and low disposal costs. A systemic and simultaneous bids performance evaluation will be gained providing a multidisciplinary approach. Furthermore, information requirements and protocols to define which quantities each bidding model must contain to enable the automated evaluation will defined along with KPIs useful to check project's environmental impact and the proposed approach validity, compared to other approaches.

3.5.1. CAM criteria in MEAT tender and case studies

The first case study is the Design-Bid procurement for the final design and construction of the new primary school in Melzo (MI), involving a total budget of €5 M for the construction of a single building hosting 500 students in 3'523 square meters. The project was developed in 2015 without including CAM application, but only the control of hazardous waste as required by the regulations of the time. BIM was applied in the design phase as well as in the drafting and management of the tender to minimize environmental impact [29]. Environmental criteria amounted at more than 40 points and the

waste management criteria directly and indirectly involved 15 out of 100 points. The second case study concerns the Design-Bid procurement for the final design and construction of the Inveruno school complex (MI). The call for proposal ended in 2020, it had a higher level of complexity with a total budget of €15 M for three building complex hosting 675 students in 7'477 square meters, in addition to the 240 hosts of the Auditorium. The project area was as a brownfield according to Lombardy Region regulation and the project involved a significant demolition phase. Environmental and CWD management criteria provided the assignment of 27 out of 100 points.

Design-Bid procurements imply the use of MEAT evaluation introduced by D. Lgs. 50/2016 to consider the quality/price ratio calculated throughout the building lifecycle. Accordingly, bids evaluation is based on quantitative and qualitative criteria, linkable to qualitative or quantitative classes so that objective alphanumerical criteria and their quality assessment is based on defined rankings. The innovative approach will be applied to evaluate bids according to their waste management and environmental impact (Table 1).

Table 1

Selected criteria and sub-criteria involved in the evaluation of bids waste management

Categories	Criteria	Sub-criteria	Evaluation sub-criteria
A	Passive elements requirements	A.2 Building materials requirements	A.2.1 - Distance to the production site of the materials A.2.3 - Degree of materials maintenance
		A.3 Environmental requirements	A.3.1 - Contractor certification according to UNI EN ISO 14001 A.3.2 - Producers certification according to UNI EN ISO 14001
C	Construction site	C.2 Constructive solutions and site management	C.2.2 - Construction site layout C.2.3 - Waste management

3.5.2. Automated waste management criteria evaluation workflow

Figure 2 shows the overall waste quantity evaluation process. Bidders will upload their offers through the Web of Linked Data platform as IFC models developed accordingly to the information requirements defined.

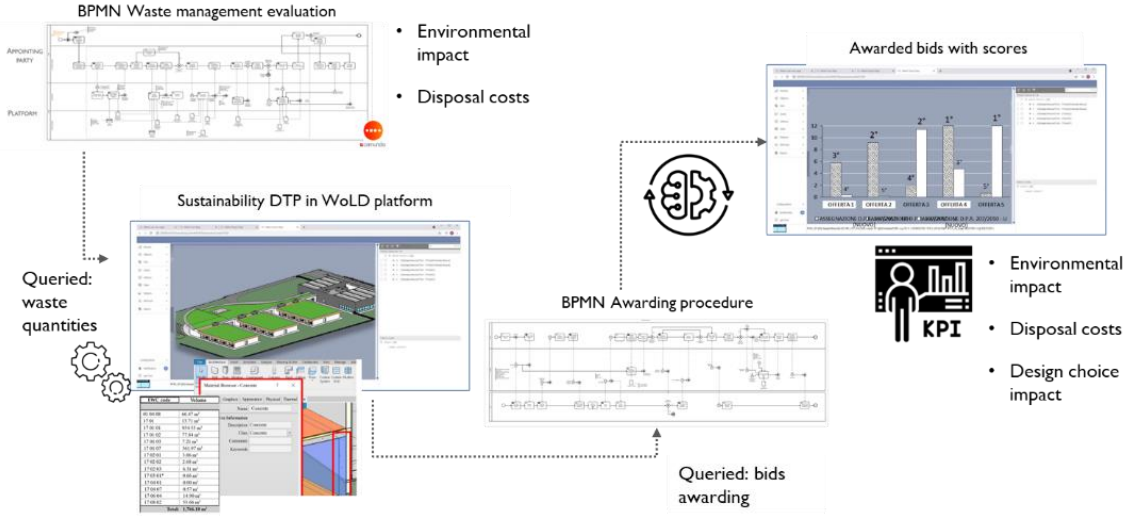

Figure 2: Overview of the waste management criteria evaluation process through the Web of Linked Data platform.

Then they will be translated and stored in RDF together with process models and other needed data. When the platform receives the request to check and evaluate waste management criteria, the related BPMN process is recalled, enabling a query to extrapolate the Sustainability DTP of each bids which contains waste quantities classified accordingly to European Waste Codes (EWC) and disposal costs. In particular, each bid model must contain waste quantities divided and weighted according to four percentage for: reusing, recycling, landfilling of hazardous and non-hazardous waste.

Then, the bids awarding process based on MEAT and multicriteria analysis is recalled and requires the interaction with the selected AI algorithm to evaluate waste quantities, their disposal costs and environmental impact, in addition to assign a score depending on the given weight in tender documents. AI will be exploited also to optimize the criteria weighting, considering the impact that a change input has on the global and single performances, depending on which criteria should be stressed more. So, it will be possible to visualize bids awarding and defined KPIs to compare this method with previous ones. The step forward concerns the use of open standards, required by the most recent regulations, the automated and data-driven method in addition to a better-defined IM approach.

The methodology is still at theoretical level and the results are discussed as expected outcomes to be whether confirmed or not through the PoC. The global worth lies in the full digitalization, shortening and transparency of the tendering phase, while the disruptive worth concerns the leveraging of an innovative approach exploiting DTPs and AI through an open-source, distributed digital framework and automatize sustainability criteria evaluation in Design-Bid procurement. Adopting a PLM perspective and defining valuable building DTPs suitable to develop actual DTIs to constantly monitor the identified KPIs throughout the building lifecycle, an actual GPP could be provided by pursuing the highest possible degree of sustainability in terms of performance, use of resources and lifecycle costs. A revolution in current public procurement procedures which prevent to exploit simulation models to evaluate bids. Table 2 shows the comparison between the main features of current evaluation approach and the proposed one. Currently, the experts commission is central and judging bids based on own professional experiences, with poor objectivity. The proposed method, based on the evidence provided by performance simulation through the DTPs system holistic view, foresees commissioners with a marginal, notarial role with an improvement in objectiveness and costs reduction, as well as the easier identification of the most sustainable solution. A powerful digital simulation tool (i.e. the DTPs system) will be exploited to handle bids evaluation. Thanks to the formalization and digitalization of the processes involved in MEAT procedure, greater objectivity and transparency will be provided. Furthermore, the key role of the Public Client in the green and digital transition becomes evident as the Appointing Party becomes an active part of the evaluation process, defining clear information requirements and avoiding receiving random bidding documents. Moreover, performances will be evaluated with a homogeneous, multidisciplinary and systemic method, as soon as the bidders upload their offers on the web-based platform. Offers can be simultaneously evaluated with a drastic reduction of tender assignment time, switching from an average of 5 to 20 months to few days (Table 2).

Table 2

Comparison between current tender approach and the proposed DTPs system (DTPS)

	Current approach	DTPS perspective
Evaluator	Judging commission	Web of Linked Data platform, commission partial actions
Tools	Excel sheets Professional experience	Digital microservices (Software, digital tools..)
Formats	Paper and text documents	Digital, open and machine-readable (IFC, json, xml..)
Awarding criteria weighting	Subjective, manually, based on commissioner's experience	Objective, automated through an AI system, based on single and global impacts
Performance evaluation	Siloed set of performances	Systematic and simultaneous
Tender duration	5-20 months	Strongly reduced, few days

Finally, the developed DTPs system and the collaboration between parties can enable to exploit the awarded project to furtherly maximize the potential sustainability and minimize both maintenance and construction costs before developing the DTIs system exploitable during the rest of lifecycle. The awarded DTPs system can be exploited by the Appointing Party to easily visualize the impact that design choices have on defined KPIs and project performances, enabling more effective and conscious sustainable choices. It provides a holistic view for bids project evaluation, enabling to quickly and automatically check whether the tender information requirements were met or not, avoiding shifting away from the original intent.

The sensitive analysis conducted by an AI system enables the formalization of the existent direct and hidden links between project performances, supporting more aware and effective design choices starting from the design phase. It will enable to promptly understand how the modification of an input might affect both the DTPs involved and the global performance. As the DTPs are simulated, it could be defined a hierarchy among the award criteria and KPIs based on their impact on project performance, costs and sustainability, optimizing MEAT evaluation method and information requirements for valuable DTPs. This lead to define trustworthy standards, information, and process management protocols for the tendering phase.

4. Conclusion

The paper tackled the overcoming of current BIM-based approaches towards a PLM perspective borrowing the DTP as conceptualized by Grieves and leveraging it to fully digitalize and shorten Design-Bid tender procedures with MEAT. A replicable methodology is proposed to develop DTs starting by the tender phase, providing a holistic approach for project performance optimization through a DTPs system which can be exploited to evaluate and award the optimal bid with respect to the client's requests and regulations, and to the overall sustainability.

The boundaries of the research were defined, among them the principal ones are the framing in Design-Bid procurements with MEAT and the developed DTP which must be a "reusable" prototype throughout the whole building lifecycle to provide the DTIs for other phases. The replicable methodology is developed to be used through a Web of Linked Data platform in the aim to develop DTPs with a highly scalable and enrichable information structure. Moreover, it enables to extrapolate and link together several correlated DTPs, resulting in a DTPs system which enables the systemic evaluation of performances. There are many challenges along with the advantages proposed. Among them the identification of information requirements and ontologies for each VDTP needed, due to the numerous and complex domains integrated in a construction project. A replicable and scalable approach is adopted, and the proposed methodology will be tested through a PoC on two real Design-Bid Italian procurements previously exploited in another work to promote waste reduction and resources valorisation. The aim is to extend previous work in a more holistic, automated approach which includes further CAM criteria evaluation. The CAM criteria to be evaluated were identified and expected outcomes and results are discussed, illustrating how a DTPs system could enable sustainability criteria automated evaluation and increasing both GPP adoption and digitalization enhancement in tendering processes. Another challenge concerns the disruptive transition from to the proposed approach which ensures full digitalization and transparency among stakeholders. This is due both to the closeness of the sector and current Italian regulations. Nonetheless, the evaluation on real case studies is meant to demonstrate the system validity and propose a twisting to the current evaluation method, providing a more objective, shortened, sustainable and transparent one. It is also identified the crucial issue to integrate the best AI system to conduct sensitivity analysis and identify direct and hidden links between the inputs. Thus, the significant ones with respect to award criteria and defined KPIs could be formalized, enabling to understand almost in real-time how a change in design choices influence the overall and the single performance.

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