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A CUSTOMIZED DATA ENVIRONMENT FOR SMALL AND MEDIUM CONSTRUCTION ENTERPRISES

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Abstract

The architecture, engineering, and construction supply chain is predominantly composed of small and medium enterprises (SMEs). Despite the growing adoption of digital tools such as Building Information Modeling (BIM), SMEs often face challenges streamlining these tools with existing enterprise resource planning (ERP) systems. This paper presents a study that worked with an SME to develop a “customized data environment”, inspired by common data environment approaches, linking their BIM and ERP workflows. The paper describes the action research cycle used to develop the prototype. Insights into both the tool and the process evolution will help other SMEs facing similar integration challenges.

Introduction

Digital transformation remains a significant challenge for the architecture, engineering, and construction (AEC) sector (Lu, 2017). Small and medium-sized enterprises (SMEs), which dominate the construction supply chain, particularly struggle to streamline their digital value chains (Agostini and Nosella, 2019; Kouch et al., 2018). The transition to digital environments requires significant investments and process changes (Mittal et al., 2018). Compared to larger companies, SMEs have fewer resources and expertise to drive digitalization in parallel with their core business. In addition, they are often dependent on the tools chosen by partners on a project-by-project basis.

The first step—digitalizing the core business process—is usually the hardest for SMEs (Mittal et al., 2018). As of today, most SMEs use enterprise resource planning (ERP) systems to manage resource-related processes such as ordering, planning, and accounting (Zach et al., 2014). ERP systems provide a solid foundation for integrating firm-level data with external data typically managed with building information modeling (BIM) processes across planning, production, and execution (Santos, 2009; Gavali and Halder, 2020). For example, Wang et al. (2019) proposed a material estimation system that captures data from BIM files and converts it into ERP readable data for the purpose of material estimation.

To optimize business processes and improving quality, SMEs would have a digital solution that integrates BIM visual data with their extant ERP system. This would enable production and procurement teams, familiar with ERP data, to benefit from enhanced geometric visualization linked to it. However, linking information at different levels of granularity, such as geometric data versus production data at different stages, remains a challenge when attempting BIM-ERP integration (Babič et al., 2010). Faced with similar challenges, a 100-employee SME specializing in semi-custom façade elements based on prefabricated elements approached us to explore possible solutions. The goal was to develop an internal platform that integrates geometric and project data across departments, and thereby breaks down silos. Using an action research approach (introduced in the methodology section), we investigated a solution to connect visual model data with their ERP data. The paper presents the solution we developed based on what we refer to as a *customized data environment*. The idea originated from the concept of the common data environment (CDE), which facilitates collaboration between project stakeholders by collecting and exposing relevant project data as a single source of truth (ISO, 2018). CDEs can use a multitude of tools, and various market-ready solutions are already available (Jaskula et al., 2024). However, unlike CDEs that mainly serve as platforms for project stakeholders who collaborate with one another, the goal was here to integrate the internal processes of a single SME. Since internal tools and processes are often unique, and because market-ready tools can be costly and likely to create a dependency on software vendors, a customized platform was developed. This approach proved promising, and the lessons learned may benefit other SMEs facing similar challenges.

Methodology

This study used the action research approach outlined in Staron (2020) to develop the described customized data environment for a construction SME (Figure 1). Action research is a newer empirical method in software engineering that emphasizes intervention (as in experiments), context (as in case studies), and learning, thereby addressing some of the usual challenges in software engineering experimentation, such as finding participants with industry

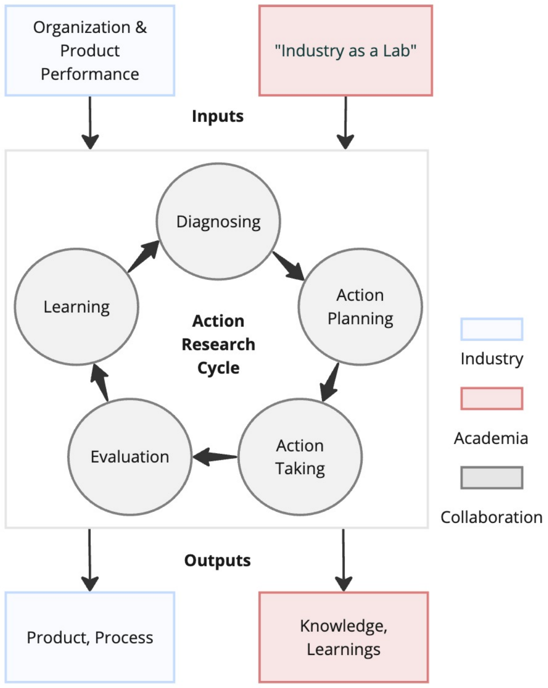


Figure 1: Action research approach. (Figure redrawn based on Staron (2020))

experience; using realistic, scalable experimental objects; and avoiding non-representative contexts caused by treatment isolation (Staron, 2020). Action research uses "industry as a laboratory" to collaboratively improve organizational and product performance through software engineering. The output typically includes both a product and knowledge.

Prototype Development

Diagnosing: Current Workflow and Tools

The first phase of the action research cycle emphasizes understanding the context. Opinions are gathered and symptoms identified. Discussions with practitioners explore the situation and determine the specific challenge to be addressed (Staron, 2020). Therefore, we started by analyzing the current workflow and tools of the SME to identify bottlenecks and integration problems.

The SME's traditional modeling workflow involves frequent switching between different representations and dimensions, as illustrated in Figure 2. The process starts with a 2D AutoCAD model from the architect, which the R&D team uses to obtain the panel dimensions. The design and engineering team then manually converts these dimensions into 2D abstract panel drawings of the major panel types, primarily using *AutoCAD* for geometry and Excel for panel parameters. Depending on the project, LOD300 3D model files are also created using *SolidWorks*. The workflow relies on standardized parameters to differentiate panel types, with new types developed from existing templates. Assemblies are manually instantiated, leading to duplicate entries in the cloud database. Renaming assemblies, sub-assemblies, and parts is a semi-manual, Excel-based process that often causes errors due to duplication and naming inconsistencies. Finally, the production team integrates project-specific façade details into a basic 3D model, which can generate LOD450 models when required or requested by the customer. They then semi-manually create milling files and manufacturing code for the machines. For field installation, the company relies on printed plans manually created by the design and engineering team.

The company uses the *Sage* ERP system but lacks integration with BIM, leaving order, production, fabrication, and installation entries disconnected from the visual model. For example, the design and engineering team manually extracts key parameters into Excel, which the procurement team then uses for cost and order calculations.

As different digital tools are used at each stage without seamless integration, the SME overall employs a partially digital workflow but struggles with inconsistent data management and siloed information. Data transfer relies heavily on file-based exchanges via email or cloud servers. The company conducts extensive manual checks at each stage to maintain quality and ensure content accuracy and consistent file naming.

A recent milestone alongside this research was the rollout of the *3Dexperience* platform for collaboration and *Catia* CAD software for modeling. However, these tools are primarily used by the design and engineering team. Moreover, the *3Dexperience* platform presents usability challenges due to its complex functionality and limited alignment with internal processes, making it difficult to use as an interface between geometry and resource planning as initially intended.

Conducting the above analysis of the SME's current workflow made it apparent that an additional data integration tool is needed to, in the SME's words, "democratizes access" to information about the whole workflow. We identified the following key capabilities as those most valuable for implementation in the action phase: (1) automatically inherit panel parameters from simple 3D models; (2) visually recognize and classify panel types based on qualitative and quantitative parameters; (3) automatically name elements according to a customization table; (4) automate quantity take-off (QtO) and bill of quantity (BoQ) generation; (5) create placeholders and routines to generate geometric panel models, preventing duplication; and (6) allow users to quickly access both geometric and ERP panel data for improved fabrication, delivery, and field installation planning.

Action Planning: Data Environment Approach

Based on the above diagnosis, we closely cooperated with the company in the action planning phase (Staron, 2020) to develop a custom data environment unifying previously siloed and disjointed workflows. The goal was not to replace the existing modeling and ERP software pipeline but to help make the information from both workflows available to the entire organization. Inspired by the growing

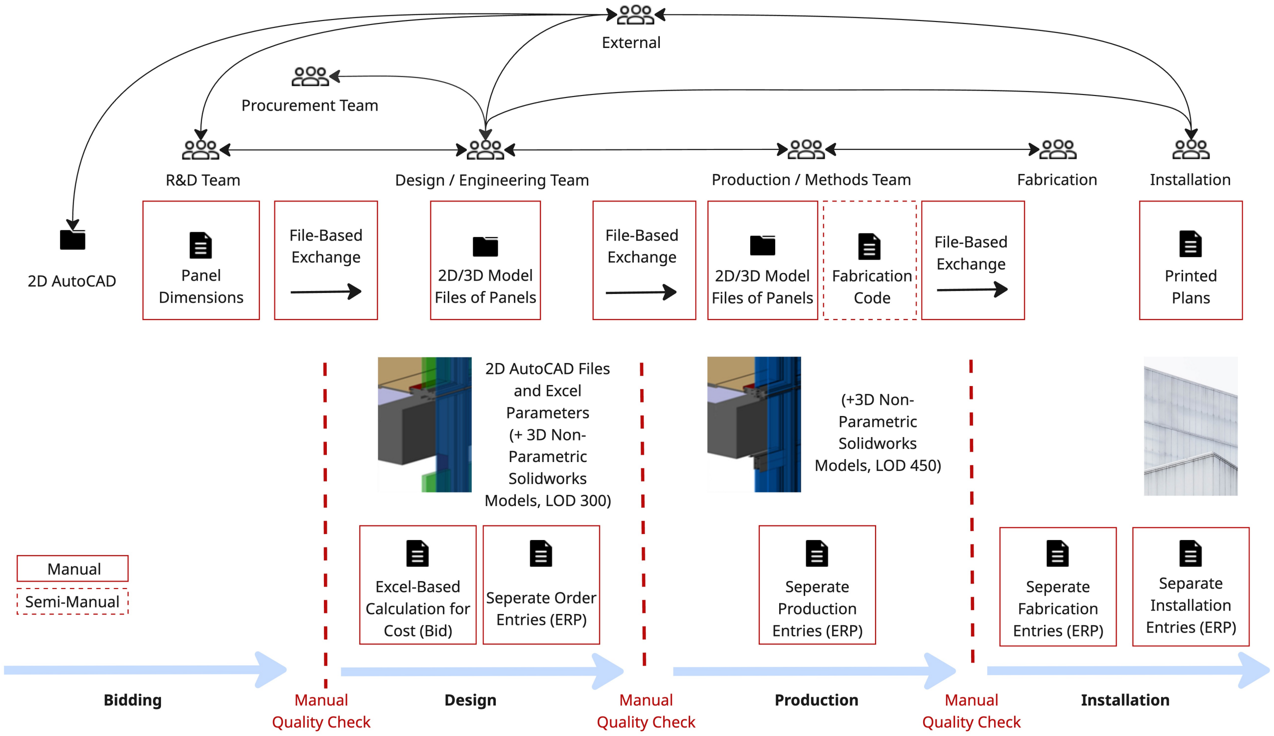


Figure 2: Diagnosing: The SME's current workflow for producing façade elements based on digital models and ERP data.

adoption of cloud-based CDEs, we decided to base our approach to data integration on a similar concept but to tailor it to the specific needs of the SME. Reviewing the current state of the art for data management, we formulated the following key principles to guide implementation:

Decomposition

Decomposition techniques separate semantic and geometric data to improve interoperability (Karan and Irizarry, 2015). Allowing authoring software to connect to the data environment and process different kinds of data independently overcomes the challenge of integrating design (geometric data) and process information (semantic data) in a single environment (Jiao et al., 2013).

Object-oriented Models

By removing rigid table schemas, object-based NoSQL databases offer greater flexibility than traditional SQL databases, supporting cloud-based BIM platforms that require flexible data storage to support semantic enrichment and customizable parameter structures (Sacks et al., 2017). In consequence, such object-based databases are increasingly being used to improve BIM component querying capabilities (Wu et al., 2019).

Modularity

A modular approach across data sets and processes prevents high complexity and system bloat, both technically and methodologically. Given the limited financial and human resources of SMEs and their constantly changing processes (Bouwman et al., 2019), the platform must be able to evolve incrementally over time. Similar to microservice architectures (Krylovskiy et al., 2015), the customized data platform should follow as modular an approach as possible on both the front- and back-end.

Following these principles, Figure 3 shows the envisaged high-level technical architecture. A web-based platform portal (front-end) should serve as a simple user access point. The platform should then expose the various control components available based on user permissions. These should include a model visualizer that imports BIM models, thereby exposing panel geometry to those unfamiliar with 3D modeling; a parameter list with query capabilities that makes it easy to edit panel parameters based on ERP data; additional components like an automatically generated BoQ; and support for project and quality-document management. The back-end should provide core functionality to support these components. It must store user data, manage roles and permissions, store geometric model data, and offer process capabilities to interact with the model. Additionally, the back-end should store product-related parameter data that intersects with visual BIM data and ERP data as well as implement the operations that enable queries.

Action Taking: Development of the Prototype

In the action phase (Staron, 2020), we developed the prototype according to the outlined approach and diagnosed the functionalities in constant feedback with the SME. Due to the focus in this paper on the overall approach rather than technical details, the following description of the proto-

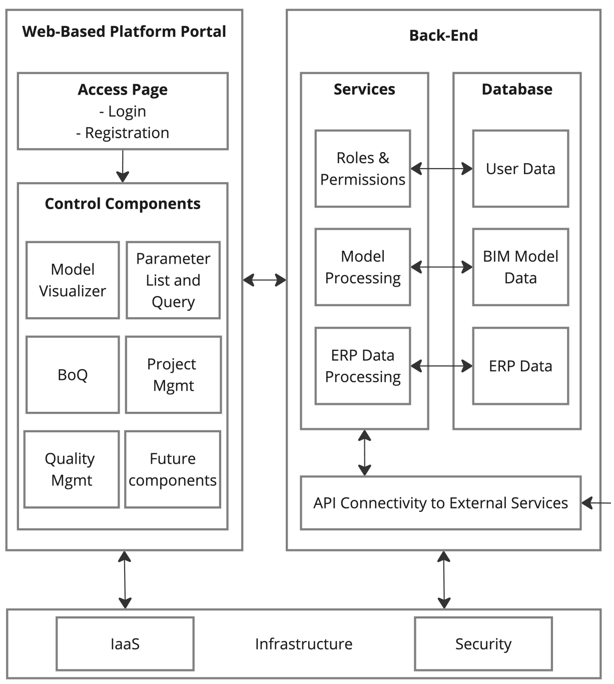


Figure 3: Action Planning: The envisioned technical architecture for the customized data environment.

type's front-end and back-end addresses technical aspects at an intentionally high level.

Front-End

The platform portal was developed as a single-page application built with the Angular framework. An authentication page asks for the login credentials and exposes the various control components. For each project, there are two main interfaces: the visualization interface and the data interface.

The most important interface is the visualization interface (Figure 4). The main window visualizes an imported model using *Autodesk Platform Service* integration (formerly *Autodesk Forge*). The visual model makes it possible to query façade elements by coloring them according to different parameters. This function of the visualization interface exposes all relevant parameters and documents linked with one or multiple panels. There are different modes for this: Façade Mode supports design iteration by displaying parameters in specific façade segments according to BIM-model data; ERP Mode provides access to ERP system data, including production status, delivery progress, and installation updates; Section Mode links sections of multiple panels to stored files and PDFs.

The data interface provides enhanced functionality to add, delete, and modify the parameter data in an Excel-like tabular interface (Figure 5). Previously, the company used Excel spreadsheets for this process, so the look and feel is familiar. Linking the data interface to the object-based data store avoids data silos. It also allows customized parameter grouping and filtering for better information retrieval. Geometric and semantic data are always transferred and retrieved independently. For instance, a static table can be retrieved for a preliminary plausibility check based on project-linked semantic data, while geometric elements are viewed with a lightweight viewer. A pivot mode allows users to aggregate and sort values by occurrence and to generate BoQs. The project management component handles project creation and editing, linking the authoring software and ERP system to the platform. A semi-automated naming system was implemented to standardized the naming of façade elements.

Back-End

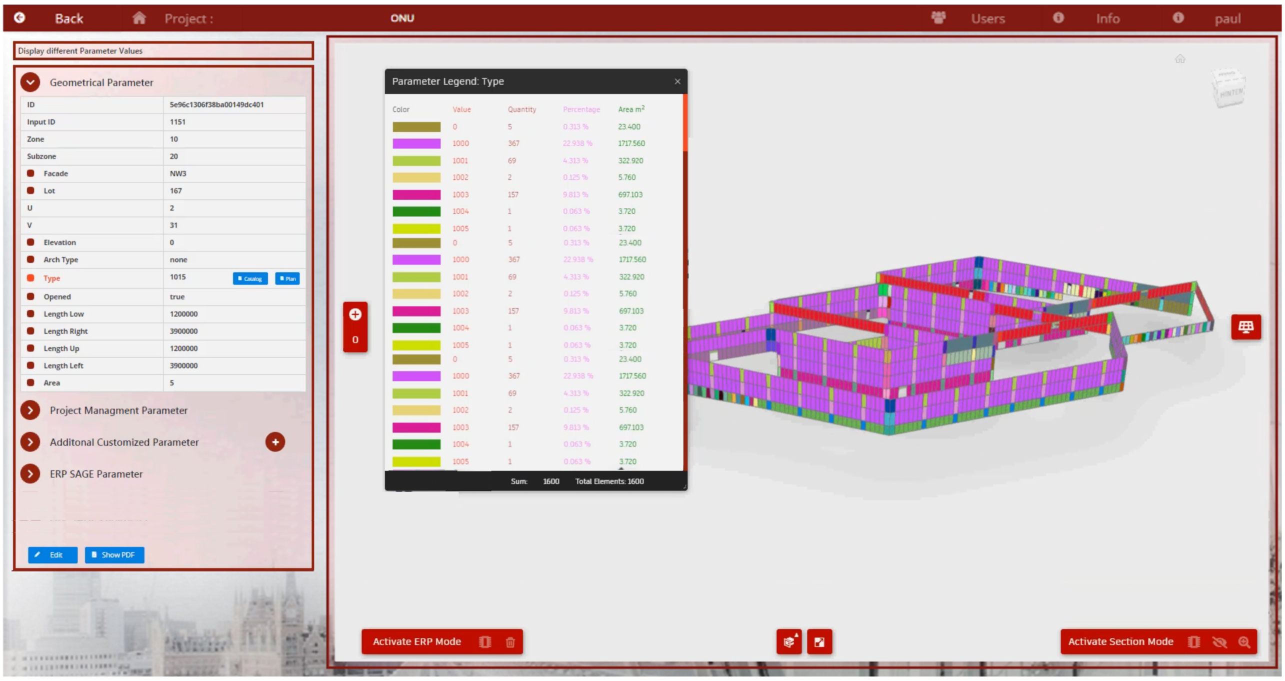
The back-end provides the services to store and process the data so that it is usable by the front-end components. The platform's back-end services were implemented as a NodeJS RESTful server. NestJS was chosen for implementation. NestJS is a progressive Node.js framework with an Angular-like architecture that leverages TypeScript, modularization, and dependency injection. Modules organize application structures by combining controllers and providers into functional units. To ensure secure login and permission, MD5 encryption generates irreversible hash values that secure storage of credentials. Additionally, a token-based system using JSON Web Tokens facilitates secure server-client communication. The roles and rights structure controls the access of user groups to certain functionalities.

Prioritizing flexibility and semantic enrichment in the definition of the internal data model, we implemented a cloud-based NoSQL database with an object-based schema (Belsky et al., 2016). MongoDB was selected because of its proven benefits for BIM datasets (Lin et al., 2016). This object-based database system clearly separates semantics and geometry. Semantic records are transferred from the authoring software to the platform via XML exports and stored with predefined schemas. Geometry is handled through the *Autodesk Platform Services* API functionality, where only a global identifier is maintained. This identifier links semantic data to geometric models, ensuring a unique relationship between database objects and geometry.

Evaluation: The Resulting Workflow

In the evaluation phase (Staron, 2020), we mapped the resulting workflow to assess whether the implemented action would adequately address the problems we diagnosed in the first phase of the action research cycle (see Figure 6). We found that the customized data environment effectuated significantly better integration and workflow transparency by making data available to the entire organizational value chain through two interfaces: the 3D model-based viewer and the table-like data interface.

The essential function of the resulting workflow was to connect 2D geometrical panel objects visualized in the 3D viewer with linked standard and project-customized semantic parameters. Data synchronicity was maintained by connecting all stakeholders to the same database, the ac-



Display different Parameter Values

Geometrical Parameter

ID	5e96c1306f38ba00149dc401
Input ID	1151
Zone	10
Subzone	20
● Facade	NW3
● Lot	167
U	2
V	31
● Elevation	0
● Arch Type	none
● Type	1015
● Opened	true
● Length Low	1200000
● Length Right	3900000
● Length Up	1200000
● Length Left	3900000
● Area	5

Project Managment Parameter

Additonal Customized Parameter

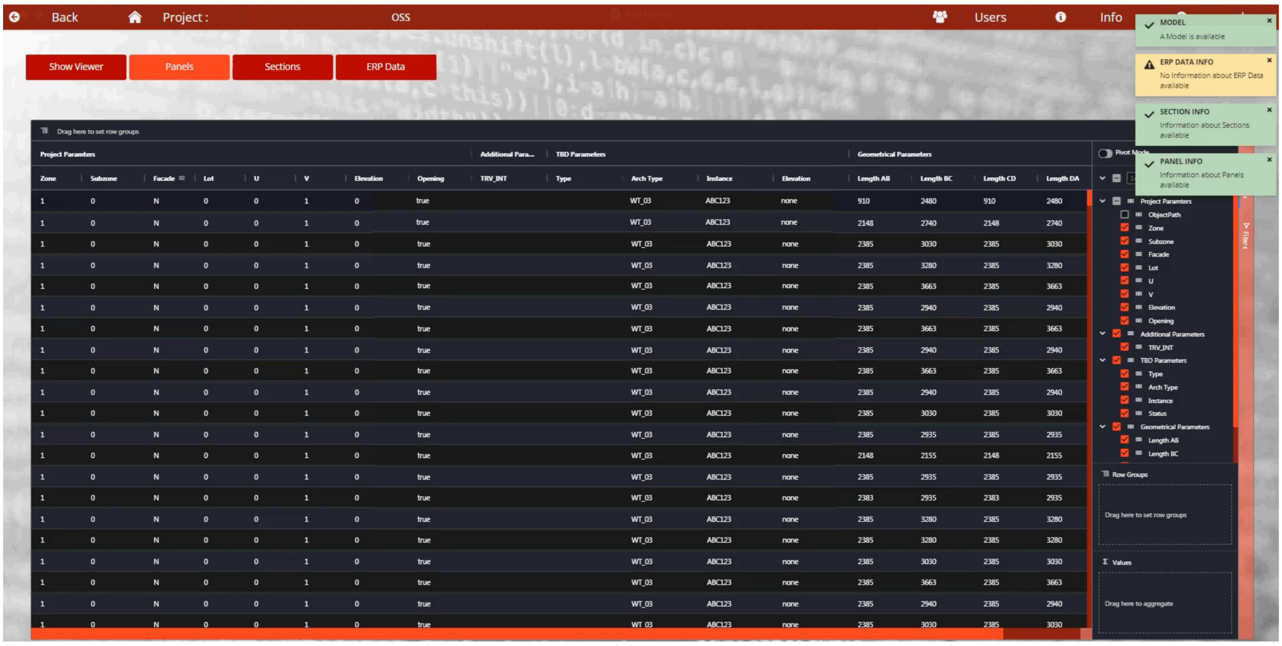
ERP SAGE Parameter

Parameter Legend: Type

Color	Value	Quantity	Percentage	Area m²
▬	0	5	0.313 %	23.400
▬	1000	367	22.938 %	1717.560
▬	1001	69	4.313 %	322.920
▬	1002	2	0.125 %	5.760
▬	1003	157	9.813 %	697.103
▬	1004	1	0.063 %	3.720
▬	1005	1	0.063 %	3.720
▬	0	5	0.313 %	23.400
▬	1000	367	22.938 %	1717.560
▬	1001	69	4.313 %	322.920
▬	1002	2	0.125 %	5.760
▬	1003	157	9.813 %	697.103
▬	1004	1	0.063 %	3.720
▬	1005	1	0.063 %	3.720
▬	0	5	0.313 %	23.400
▬	1000	367	22.938 %	1717.560
▬	1001	69	4.313 %	322.920
▬	1002	2	0.125 %	5.760
▬	1003	157	9.813 %	697.103
▬	1004	1	0.063 %	3.720
▬	1005	1	0.063 %	3.720

Sum: 1600 Total Elements: 1600

Figure 4: Action Taking: The visualization interface of the prototype loads a model viewer. It can visually query and match the panels with geometric, project, and other ERP system-related parameters. It makes a simple visual model accessible to all teams.



MODEL
A Model is available

ERP DATA INFO
No Information about ERP Data available

SECTION INFO
Information about Sections available

PANEL INFO
Information about Panels available

Project Paramters								Additional Para...	TBD Parameters				Geometrical Parameters			
Zone	Subzone	Facade	Lot	U	V	Elevation	Opening	TRV_INT	Type	Arch Type	Instance	Elevation	Length AB	Length BC	Length CD	Length DA
1	0	N	0	0	1	0	true			WT_03	ABC123	none	910	2480	910	2480
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2148	2740	2148	2740
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3030	2385	3030
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3280	2385	3280
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3663	2385	3663
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	2940	2385	2940
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3663	2385	3663
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	2940	2385	2940
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3663	2385	3663
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	2940	2385	2940
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3030	2385	3030
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	2935	2385	2935
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2148	2155	2148	2155
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	2935	2385	2935
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2383	2935	2383	2935
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3280	2385	3280
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3280	2385	3280
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3030	2385	3030
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3663	2385	3663
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	2940	2385	2940
1	0	N	0	0	1	0	true			WT_03	ABC123	none	2385	3030	2385	3030

- ☐ Project Paramters
  - ☐ ObjectPath
  - ☑ Zone
  - ☑ Subzone
  - ☑ Facade
  - ☑ Lot
  - ☑ U
  - ☑ V
  - ☑ Elevation
  - ☑ Opening
- ☑ Additional Parameters
  - ☑ TRV_INT
- ☑ TBD Parameters
  - ☑ Type
  - ☑ Arch Type
  - ☑ Instance
  - ☑ Status
- ☑ Geometrical Parameters
  - ☑ Length AB
  - ☑ Length BC

Figure 5: Action Taking: The prototype's data interface mimics the experience of Excel but improves functionality and process oversight. It links geometric and ERP data, enabling filtering and data entry based on the visual model.

cess to which was controlled with usernames and passwords. Instantaneity ensured that any database changes were immediately visible, and an intuitive interface minimized time spent searching for data. The platform also provided access to both geometric and ERP parameters, with color filters in the visual model for quick interpretation. Modifications to the data were made directly in the viewer and data interfaces using tools for data selection and modification. However, it was not possible to edit the geometry at the time of the study. Data was compared on the basis of parameters, values, or names, and comparative charts were automatically generated for analysis. Live parsing methods simplified the process of immediately extracting and easily formatting BoQs. Reusability and consistency of generated panel components was achieved through automated naming, tree structure management, and data hierarchy consolidation.

Figure 6 illustrates the new workflow with the customized

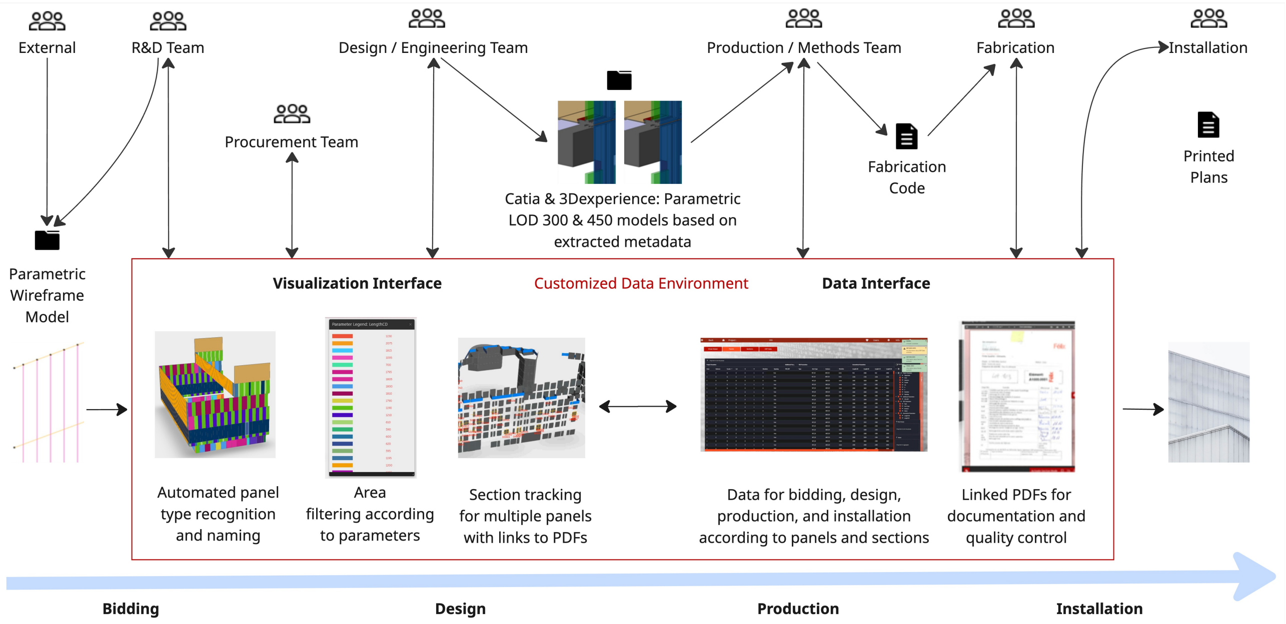


Figure 6: Evaluation: The customized data environment resulted in a more integrated workflow for façade production by democratizing access to both geometry and production data across the entire organizational value chain.

data environment for the SME across different phases. The R&D team converted the architect's BIM model into a parametric wire-frame model in *Catia*. The wire frame served as the information support to automatically generate the visual model and panel data objects. In the bidding phase, the platform supported sorting by façade panel type and generated the required metrics for QtO. In both the design and production phases, the platform created project-specific naming conventions for greater consistency. It also pre-generated models, which could then be finalized outside the platform in *Catia* and *3Dexperience* modeling environments. Fabrication code was still generated outside of the platform by the production and methods team. During production, the data environment provided detailed information—visual and commercial ERP data—on the status of individual pieces. Finally, in the installation phase, the platform linked reports and quality tests to the correct elements. Installation plans could have been digitally accessed through the web-interface but were still printed. At all times, the section tool helped coordinate information exchange by storing documents and information related to defined panel clusters in the data environment.

The customized data environment impacted the SME's processes in multiple ways. First and foremost, it achieved what the company called "democratization of data access" by making both visual and production data available to the whole organization. It gave everyone a better overall understanding of the project by channeling all information into one visual 3D interface, eliminating redundancy, and providing an accurate model to avoid the common errors of 2D representations. Instant and local queries made in the visual model simplified information searches and increased process efficiency. Now that data has been synchronized and standardized, trust in its accuracy has increased, making direct exports to modeling and ERP systems more readily accepted compared to the SME's traditional manual, error-prone processes. The platform also addressed challenges related to the different geographic locations in which the production process takes place, such as monitoring information between the factory and construction sites. Finally, web-based access simplified tracking panel fabrication and installation. Capturing information directly in the field allowed project managers to process data in real time without needing to return to the office.

Discussion

Learnings

The final part of the action research cycle is specifying what was learned (Staron, 2020). The customized data environment was successfully implemented as a prototype for internal SME use. It connected to both the ERP system and BIM-based geometry and processes. The integrated platform eliminates the need to repeatedly process and generate the same information. It empowers the SME to manage data flow and consistency. External actors are easily integrated through restricted access to the web-based interface. The platform also eliminates the need for time-consuming and error-prone email and file transfers and serves as the primary medium for information exchange. Despite these workflow improvements, at the time of review, the SME lacked confidence in sharing the new platform with external stakeholders, specifically fearing exposure of sensitive information. A second key lesson is the importance of the combination of the visualizer (see Figure 5) and the Excel-like table environment (see Figure 6) for enabling all company employees to use the platform effectively, regardless of whether one prefers a graphical interface or is accustomed to the ERP system workflow.

From both a commercial and technical perspective, a customized solution offers many benefits for the digital transformation of SMEs. With a modular approach, the implementation can be done incrementally and according to the specific needs of the SME. The platform is low cost and minimal effort compared to other all-in-one commercial solutions that may offer unused functionality. For example, a next improvement step could be to replace the chosen *Autodesk Platform Services* integration for model visualization with new and upcoming open-source viewers such as COMPAS (COMPAS, 2024). Decomposition helps overcome the challenges of connecting an ERP system lacking geometric information to a semantically aggregated model, allowing ERP data to be traced back to a geometric model. In addition, this link facilitates the automatic creation of a preliminary BoQ, even before the detailed model is developed, using the semantic information associated with the basic geometry. The object-based data model further enhances this process. It accurately reflects reality by representing the smallest elements, such as a façade glass panel, as individual data objects. Complex assemblies, like façades, are represented as multi-part datasets (so-called sections in the digital model).

Limitations and Future Research

Although the customized data environment presented in this case study was successful, it remains a single use case. Further research is needed to determine whether similar concepts can effectively support other construction SMEs. This research could be enhanced by measuring KPIs to statistically analyze the impact of the developed solution (Staron, 2020).

Data management in construction informatics is a rapidly evolving field (Bucher et al., 2024). Other emerging technologies that are potentially beneficial for customized data environments should be explored to understand their potential benefits, opportunities, and risks when applied to customized data environments. For example, linked data is increasingly being used to overcome the limitations of industry foundation classes (Bonduel et al., 2018), further improving the decoupling of geometry and semantic data, which is critical for better interoperability and data management (Rasmussen et al., 2020). The emerging impact of new artificial intelligence solutions should also be studied in relation to the proposed approach. Overall, the focus of this paper has been on the functionality and its implications to the SME's data workflow, rather than the technical details of the solution, which are subject to rapid change.

Beyond the technical, digital transformation and innovation present a series of challenges (Azzouz and Papadonikolaki, 2020). More research is needed to study the effects of integrated digital approaches, like this customized data environment, on socio-technical aspects of SMEs such as new communication needs within teams, new roles, and new organization structures.

Conclusions

To support the digital transformation of a construction façade SME, we undertook an industry collaboration using action research to develop a customized data environment that bridges the SME's BIM processes with their ERP system. The resulting prototype successfully “democratized” access to both geometric and production data. In consequence, organizational processes were streamlined and data management was simplified.

Outlining the action research cycle of the prototype, the paper provides guidance for understanding and developing customized data environments for SMEs. It draws inspiration from off-the-shelf CDE solutions that may be costly or unsuitable for the SME's unique processes. The customized and modular approach we chose demonstrates the potential to provide affordable data integration with minimal dependency on third-party vendors while allowing for future functional enhancements. For SMEs, a *customized* data environment may be the better “CDE.” Further studies are needed to validate its applicability to other SMEs and explore its impact on the broader architecture, engineering, and construction ecosystem.

Acknowledgments

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