

1 Spreadsheet Data Extractor (SDE): A Performance-Optimized, 2 User-Centric Tool for Transforming Semi-Structured Excel 3 Spreadsheets into Relational Data

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Abstract

Spreadsheets are widely used across domains, yet their human-oriented layouts (merged cells, hierarchical headers, multiple tables) hinder automated extraction. We present the Spreadsheet Data Extractor (SDE), a user-in-the-loop system that converts semi-structured sheets into structured outputs without programming. Users declare the structure they perceive; the engine broadcasts selections deterministically and renders results immediately. Under the hood, SDE employs incremental loading, byte-level XML streaming (avoiding DOM materialisation), and viewport-bounded rendering.

Optimised for time-to-first-visual, SDE delivers about **70×** speedup over Microsoft Excel when opening a selected sheet when opening a selected sheet in a large real-world workbook; under workload-equivalent conditions (single worksheet, full parse) it remains about **10×** faster, while preserving layout fidelity. These results indicate SDE’s potential for reliable, scalable extraction across diverse spreadsheet formats.

CCS Concepts

• Applied computing → Spreadsheets; • Information systems → Data cleaning; • Software and its engineering → Extensible Markup Language (XML); • Human-centered computing → Graphical user interfaces; • Theory of computation → Data compression.

Keywords

Spreadsheets, Data cleaning, Relational Data, Excel, XML, Graphical user interfaces

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1 Introduction

Spreadsheets underpin workflows across healthcare [5], nonprofit organizations [16, 20], finance, commerce, academia, and government [10]. Despite their ubiquity, reliably analyzing and reusing the data they contain remains difficult for automated systems. In practice, many real-world spreadsheets are organized for human consumption [19] and therefore exhibit layouts with empty cells, merged regions, hierarchical headers, and multiple stacked tables. While such conventions aid human reading [15], they hinder machine readability and complicate extraction, integration, and downstream analytics.

The reliance on spreadsheets as ad-hoc solutions poses several limitations:

- **Data Integrity and Consistency:** Spreadsheets are prone to errors, such as duplicate entries, inconsistent data formats, and inadvertent modifications, which can compromise data integrity. [1, 7]
- **Scalability Issues:** As datasets grow in size and complexity, spreadsheets become less efficient for data storage and retrieval, leading to performance bottlenecks. [14, 18]
- **Limited Query Capabilities:** Unlike databases, spreadsheets lack advanced querying and indexing features, restricting users from performing complex data analyses.

Transitioning from these ad-hoc spreadsheet solutions to standardized database systems offers numerous benefits:

- **Enhanced Data Integrity:** Databases enforce data validation rules and constraints, ensuring higher data quality and consistency.
- **Improved Scalability:** Databases are designed to handle large volumes of data efficiently, supporting complex queries and transactions without significant performance degradation.
- **Advanced Querying and Reporting:** Databases provide powerful querying languages like SQL, enabling sophisticated data analysis and reporting capabilities.
- **Seamless Integration:** Databases facilitate easier integration with various applications and services, promoting interoperability and data sharing across platforms.

Given the abundance of spreadsheet data and the clear advantages of database systems, there is a pressing need for tools that bridge these formats. Automated, accurate extraction from spreadsheets into relational representations is essential.

Prior work introduced a tool for extracting data from Excel files [3]. While effective, that system exhibited performance issues on large workbooks and imprecise rendering of cell geometry,

which limited usability for complex, real-world files. The user interface was also fragmented, requiring context switches between hierarchy definition and output preview.

This paper presents the *Spreadsheet Data Extractor (SDE)*, which transforms semi-structured spreadsheet content into machine-readable form. Users declare structure directly via cell selections—no programming required. The design addresses the above limitations and supports large, irregular spreadsheets with predictable, interactive performance.

1.1 Contributions

- (1) **Unified interaction.** We integrate the selection hierarchy, worksheet view, and output preview into a single interface, reducing context switches and lowering the number of required interactions.
- (2) **DOM-free, byte-level worksheet parsing.** We implement a custom parser that operates directly on the XLSX worksheet bytes, avoiding DOM construction and regex over decoded strings. This greatly reduces memory footprint and improves robustness on large/“bloated” sheets.
- (3) **Incremental loading.** Worksheets are loaded and parsed on demand from the XLSX archive, enabling near-instant open times and interactive latency on large files (quantified in §??).
- (4) **Excel-faithful rendering.** We recover row heights, column widths, and merges from XML to render worksheets closely to Excel, including text overflow behavior, which improves user orientation.
- (5) **Viewport-bounded rendering.** The renderer draws only cells intersecting the viewport; selection queries are pruned with cached axis-aligned bounding boxes. Together these keep per-frame work proportional to what is visible rather than to sheet size.

2 Related Work

The extraction of relational data from semi-structured documents, particularly spreadsheets, has garnered significant attention due to their ubiquitous use across domains such as business, government, and scientific research. Several frameworks and tools have been developed to address the challenges of converting flexible spreadsheet formats into normalized relational forms suitable for data analysis and integration as summarized in Table 1.

2.1 Aue et al.’s Converter

Aue et al. [3] developed a tool to facilitate data extraction from Excel spreadsheets by leveraging the Dart *excel* package [8] to process .xlsx files. This tool allows users to define data hierarchies by selecting relevant cells containing data and metadata. However, the approach faced significant performance bottlenecks due to the *excel* package’s requirement to load the entire .xlsx file into memory, resulting in slow response times, particularly for large files.

In addition to memory issues, the tool calculated row heights and column widths based solely on cell content, ignoring the dimensions specified in the original Excel file. This led to rendering discrepancies between the tool and the original spreadsheet. Furthermore, the tool rendered all cells, regardless of their visibility

within the viewport, significantly degrading performance when handling worksheets with large numbers of cells.

2.2 DeExcelerator

Eberius et al. [11] introduced **DeExcelerator**, a framework that transforms partially structured spreadsheets into first normal form relational tables using heuristic-based extraction phases. It addresses challenges such as table detection, metadata extraction, and layout normalization. While effective in automating normalization, its reliance on predefined heuristics limits adaptability to heterogeneous or unconventional spreadsheet formats, highlighting the need for more flexible approaches.

2.3 XLIndy

Koci et al. [12] developed **XLIndy**, an interactive Excel add-in with a Python-based machine learning backend. Unlike DeExcelerator’s fully automated heuristic approach, XLIndy integrates machine learning techniques for layout inference and table recognition, enabling a more adaptable and accurate extraction process. XLIndy’s interactive interface allows users to visually inspect extraction results, adjust configurations, and compare different extraction runs, facilitating iterative fine-tuning. Additionally, users can manually revise predicted layouts and tables, saving these revisions as annotations to improve classifier performance through (re-)training. This user-centric approach enhances the tool’s flexibility, allowing it to accommodate diverse spreadsheet formats and user-specific requirements more effectively than purely heuristic-based systems.

2.4 FLASHRELATE

Barowy et al. [4] presented **FLASHRELATE**, an approach that empowers users to extract structured relational data from semi-structured spreadsheets without requiring programming expertise. FLASHRELATE introduces a domain-specific language, **FLARE**, which extends traditional regular expressions with spatial constraints to capture the geometric relationships inherent in spreadsheet layouts. Additionally, FLASHRELATE employs an algorithm that synthesizes FLARE programs from a small number of user-provided positive and negative examples, significantly simplifying the automated data extraction process.

FLASHRELATE distinguishes itself from both DeExcelerator and XLIndy by leveraging programming-by-example (PBE) techniques. While DeExcelerator relies on predefined heuristic rules and XLIndy incorporates machine learning models requiring user interaction for fine-tuning, FLASHRELATE allows non-expert users to define extraction patterns through intuitive examples. This approach lowers the barrier to entry for extracting relational data from complex spreadsheet encodings, making the tool accessible to a broader range of users.

2.5 Senbazuru

Chen et al. [6] introduced **Senbazuru**, a prototype Spreadsheet Database Management System (SSDBMS) designed to extract relational information from a large corpus of spreadsheets. Senbazuru

Name	Technologies	Output	Accessibility	Frequency
DeExcelerator	heuristics	cleaned data	partially open source no access to GUI code	last publication 2015
FlashRelate	AI programming-by-example	cleaned data	proprietary, no access	last publication 2015
Senbazuru	AI	cleaned data	partially open source no access to GUI code	last commit 2015
XLIndy	AI	cleaned data	no access	discontinued
TableSense	AI	diagrams	proprietary, no access	last commit 2021
Aue et al. (converter)	User-centric Selection-Workflow	cleaned data	no public repository	last publication 2024

Table 1: Spreadsheet Data Extractor counterparts

addresses the critical issue of integrating data across multiple spreadsheets, which often lack explicit relational metadata, thereby hindering the use of traditional relational tools for data integration and analysis.

Senbazuru comprises three primary functional components:

- (1) **Search:** Utilizing a textual search-and-rank interface, Senbazuru enables users to quickly locate relevant spreadsheets within a vast corpus. The search component indexes spreadsheets using Apache Lucene, allowing for efficient retrieval based on relevance to user queries.
- (2) **Extract:** The extraction pipeline in Senbazuru consists of several stages:
 - **Frame Finder:** Identifies data frame structures within spreadsheets using Conditional Random Fields (CRFs) to assign semantic labels to non-empty rows, effectively detecting rectangular value regions and associated attribute regions.
 - **Hierarchy Extractor:** Recovers attribute hierarchies for both left and top attribute regions. This stage also incorporates a user-interactive repair interface, allowing users to manually correct extraction errors, which the system then generalizes to similar instances using probabilistic methods.
 - **Tuple Builder and Relation Constructor:** Generates relational tuples from the extracted data frames and assembles these tuples into coherent relational tables by clustering attributes and recovering column labels using external schema repositories like Freebase and YAGO.
- (3) **Query:** Supports basic relational operations such as selection and join on the extracted relational tables, enabling users to perform complex data analysis tasks without needing to write SQL queries.

Senbazuru's ability to handle hierarchical spreadsheets, where attributes may span multiple rows or columns without explicit labeling, sets it apart from earlier systems like DeExcelerator and XLIndy. By employing machine learning techniques and providing user-friendly repair interfaces, Senbazuru ensures high-quality extraction and facilitates the integration of spreadsheet data into relational databases.

2.6 TableSense

Dong et al. [9] developed **TableSense**, an end-to-end framework for spreadsheet table detection using Convolutional Neural Networks (CNNs). TableSense addresses the diversity of table structures and layouts by introducing a comprehensive cell featurization scheme, a Precise Bounding Box Regression (PBR) module for accurate boundary detection, and an active learning framework to efficiently build a robust training dataset.

While **DeExcelerator**, **XLIndy**, **FLASHRELATE**, and **Senbazuru** focus primarily on transforming spreadsheet data into relational forms through heuristic, machine learning, and programming-by-example approaches, **TableSense** specifically targets the accurate detection of table boundaries within spreadsheets using deep learning techniques. Unlike region-growth-based methods employed in commodity spreadsheet tools, which often fail on complex table layouts, TableSense achieves superior precision and recall by leveraging CNNs tailored for the unique characteristics of spreadsheet data. However, TableSense focuses on table detection and visualization, allowing users to generate diagrams from the detected tables but does not provide functionality for exporting the extracted data for further analysis.

2.7 Comparison and Positioning

A direct head-to-head comparison was not possible due to the lack of artifacts, because for the UI-oriented systems **FLASHRELATE**, **Senbazuru**, **XLIndy**, and **DeExcelerator**, we contacted the authors mentioned in the publications to obtain research artifacts (source code, UI prototypes). As of the submission deadline, we had either not received any responses or that the project was discontinued; we could not find publicly accessible UI artifacts or runnable packages.

Moreover, unlike the aforementioned tools that rely on heuristics, machine learning, or AI techniques—which can introduce errors requiring users to identify and correct—we adopt a user-centric approach that gives users full control over data selection and metadata hierarchy definition. While this requires more manual input, it eliminates the uncertainty and potential inaccuracies associated with automated methods. To streamline the process and enhance efficiency, our tool includes user-friendly features such as the ability to duplicate hierarchies of columns and tables, and to move them

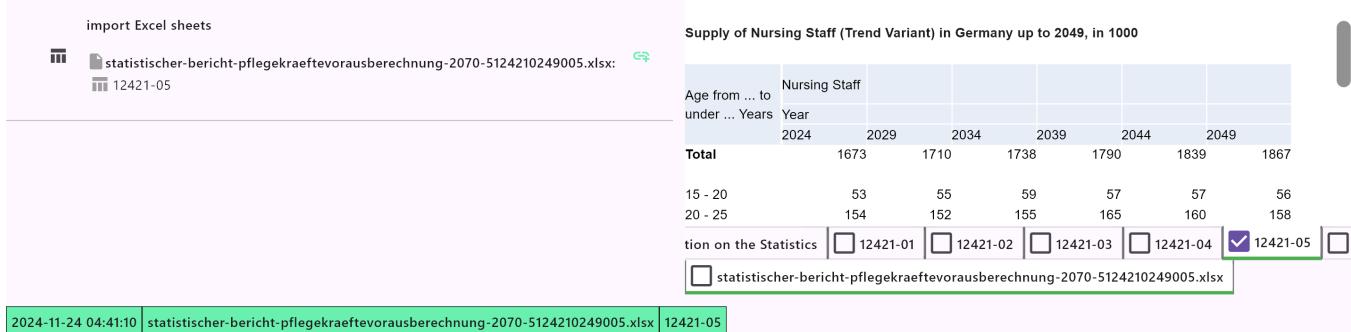


Figure 1: The SDE Interface Overview.

over similar structures for reuse, reducing the need for repetitive configurations.

By combining the strengths of manual control with enhanced user interface features and performance optimizations, our tool offers a robust and accessible solution for extracting relational data from complex and visually intricate spreadsheets. These enhancements not only improve performance and accuracy but also elevate the overall user experience, making our tool a valuable asset for efficient and reliable data extraction from diverse spreadsheet formats.

3 Design Philosophy

Spreadsheet tables are heterogeneous, noisy, and locally structured in ways that are hard to infer reliably with fully automatic extraction. Our goal is not to replace the analyst with an opaque model, but to *amplify* their judgment: the user points to the structure they already perceive (regions, labels, value columns), and the system guarantees a faithful, auditable transformation into a relational view. Instead of automatically extracting and then searching for mistakes, we invert the workflow: *select first, broadcast deterministically, render immediately*. This keeps discrepancies visible at the point of selection, where they can be corrected with minimal context switches.

We enforce three invariants: (i) **Provenance**: every emitted tuple is traceable to a set of visible source cells via an explicit mapping; (ii) **Stability**: small edits to selections induce bounded, predictable changes in the output (no global re-writes); (iii) **Viewport-bounded cost**: interactive operations run in time proportional to the number of cells intersecting the viewport, not the worksheet size. The parsing, indexing, and rendering subsystems are organized to uphold these invariants at scale.

User-Centric Data Extraction. The core interaction in the SDE lets users declare structure directly on the spreadsheet canvas and organize it into a hierarchy that drives a deterministic transformation into a relational view.

Hierarchy Definition. Users select individual cells or ranges (click, Shift-click for multi-selection). Each selection denotes either data (values) or metadata (labels/headers). Selections are arranged into a hierarchical tree: each node represents a data element; child nodes

represent nested data or metadata. This hierarchy specifies how the SDE broadcasts selections into rows/columns in the output.

The interface supports flexible management: users drag-and-drop nodes to reparent or reorder the hierarchy when a different organization is more appropriate. Users can also introduce *custom nodes* with user-defined text to encode metadata that is implicit in the spreadsheet but absent from cell contents.

Reusability and Efficiency. To reduce repetitive work on sheets with repeated layouts, users can duplicate an existing selection hierarchy and apply it to similar regions. When moving a hierarchy, some cells may need to remain fixed (e.g., vertically stacked tables where only the topmost table repeats header rows). In *DuplicateAndMove* mode, the SDE provides a *lock* function: users freeze specific cells while relocating the rest of the hierarchy. Locks can be toggled via the lock icon at the top-left corner of a cell or next to the corresponding selection in the hierarchy panel; locked cells remain stationary while other selections shift accordingly (see Figure 4 in 4). Already-locked selections are visually indicated and can be unlocked at any time.

4 Example Workflow

Consider a spreadsheet containing statistical forecasts of future nursing staff availability in Germany [17]. Figure 1 shows the SDE interface, which consists of three main components:

Hierarchy Panel (Top Left): Displays the hierarchy of cell selections, initially empty.

Spreadsheet View (Top Right): Shows the currently opened Excel file and the currently selected worksheet for cell selection.

Output Preview (Bottom): Provides immediate feedback on the data extraction based on current selections.

4.1 Selection of the First Column

The user adds a node to the hierarchy and selects the cell containing the metadata "Nursing Staff" (Figure 2). This cell represents metadata that is common to all cells in this worksheet. Therefore, it should be selected first and should appear at the beginning of each row in the output CSV file.

Within this node, the user adds a child node and selects the cell "Total", which serves as both a table header and a row label. This selection represents the table header of the first subtable. The user adds another child node and selects the range of cells containing

The screenshot shows the SDE interface with a sidebar on the left containing file history and a main workspace on the right. In the workspace, a table titled "Supply of Nursing Staff (Trend Variant) in Germany up to 2049, in 1000" is displayed. A context menu is open over the first column of the table, specifically over the cell "2024". The menu includes options like "encapsulate", "enter value manually", "move and duplicate", "copy cell selection", "copy task", and "duplicate task". The "move and duplicate" option is selected. A preview area below the table shows the result of the duplication: three additional columns are added to the right of the original "2024" column, labeled "2029", "2034", and "2039". The "move and duplicate" button in the menu has a checked checkbox.

Age from ... to under ...	Years	Nursing Staff					
	2024	1673	2029	2034	2039	2044	2049
Total		1673	1710	1738	1790	1839	1867
15 - 20		53	55	59	57	57	56
20 - 25		154	152	155	165	160	158

Figure 2: Selection of the First Column Metadata

row labels (e.g., "Total", "15-20", "20-25" and so forth) by clicking the first cell and shift-clicking the last cell.

A further child node is then placed under the row labels node, and the user selects the year "2024". Subsequently, an additional child node is created beneath the year node, and the user selects the corresponding data cells (e.g., "1673", "53", "154", etc.).

At this point, the hierarchy consists of five nodes, each—except the last one—containing an embedded child node. In the upper-right portion of the interface, the chosen cells are displayed in distinct colors corresponding to each node. The lower area shows a preview of the extracted output. For each child node, an additional column is appended to the output. When multiple cells are selected for a given node, their values appear as entries in new rows of the output, reflecting the defined hierarchical structure.

4.2 Duplicating the Column Hierarchy

To avoid repetitive manual entry for additional years, the user duplicates the hierarchy for "2024" and adjusts the cell selections

This screenshot shows the SDE interface with a sidebar on the left and a main workspace on the right. The workspace displays a table with the same structure as Figure 2. A context menu is open over the "2024" cell in the first column. The menu includes options: "encapsulate", "enter value manually", "move and duplicate", "copy cell selection", "copy task", and "duplicate task". The "move and duplicate" option is highlighted. Below the table, a preview area shows the result of duplicating the "2024" column: three new columns ("2029", "2034", "2039") have been added to the right of the original "2024" column. The "move and duplicate" button in the menu has a checked checkbox.

Age from ... to under ...	Years	Nursing Staff					
	2024	1673	2029	2034	2039	2044	2049
Total		1673	1710	1738	1790	1839	1867
15 - 20		53	55	59	57	57	56
20 - 25		154	152	155	165	160	158

Figure 3: Invoking the "move and duplicate" feature on the 2024 column node.

to include data for subsequent years (e.g., "2025", "2026") using the "Move and Duplicate" feature.

To do this, the user selects the node of the first column "2024" and right-clicks on it. A popup opens in which the action "move and duplicate" appears, which should then be clicked, as shown in Figure 3.

4.3 Duplicating the Table Hierarchy

Subsequently, a series of buttons opens in the app bar at the top right, allowing the user to move the cell selections of the node as well as all child nodes, as seen in Figure 4. By pressing the button to move the selection by one unit to the right, the next column is selected. However, this would also deselect the first column since the selection was moved. To preserve the first column, the "move and duplicate" checkbox can be activated. This creates the shifted selection in addition to the original selection. The changes are only applied when the "accept" button is clicked. The next columns could also be selected in the same way. But this can be done faster, because instead of moving the selection and duplicating it only once, the "repeat" input field can be filled with as many repetitions as there are columns. By entering the number 5, the selection of the first

This screenshot shows the SDE interface with a sidebar on the left and a main workspace on the right. The workspace displays the same table as previous figures. A context menu is open over the "2024" cell in the first column. The menu includes options: "encapsulate", "enter value manually", "move and duplicate", "copy cell selection", "copy task", and "duplicate task". The "move and duplicate" option is highlighted. Below the table, a preview area shows the result of duplicating the "2024" column: three new columns ("2029", "2034", "2039") have been added to the right of the original "2024" column. The "move and duplicate" button in the menu has a checked checkbox. Above the table, a toolbar shows buttons for moving selection left/right, a checked checkbox for "move and duplicate", a "repeat" input field set to "5", and accept/cancel buttons.

Age from ... to under ...	Years	Nursing Staff					
	2024	1673	2029	2034	2039	2044	2049
Total		1673	1710	1738	1790	1839	1867
15 - 20		53	55	59	57	57	56
20 - 25		154	152	155	165	160	158

Figure 4: Moving the hierarchy one cell to the right while adjusting the number of repetitions to duplicate the column selection.

Supply of Nursing Staff (Trend Variant) in Germany up to 2049, in 1000

Age from ... to under ... Years	Nursing Staff						
	Year	2024	2029	2034	2039	2044	2049
Total	1673	1710	1738	1790	1790	1839	1867
15 - 20	53	55	59	57	57	56	56
20 - 25	154	152	155	165	160	160	158

tion on the Statistics 12421-01 12421-02 12421-03 12421-04 12421-05

statistischer-bericht-pflegekraeftevorausberechnung-2070-5124210249005.xlsx

2024-11-24 04:47:51	statistischer-bericht-pflegekraeftevorausberechnung-2070-5124210249005.xlsx	12421-05	Nursing Staff	Total	Total	2024	B6	1673
2024-11-24 04:47:51	statistischer-bericht-pflegekraeftevorausberechnung-2070-5124210249005.xlsx	12421-05	Nursing Staff	Total	15 - 20	2024	B7	53
2024-11-24 04:47:51	statistischer-bericht-pflegekraeftevorausberechnung-2070-5124210249005.xlsx	12421-05	Nursing Staff	Total	20 - 25	2024	B8	154

Figure 5: Resulting Hierarchy After Move and Accept

column is shifted 5 times by one unit to the right and duplicated at each step.

The user reviews the selections in the spreadsheet view, where each selection is highlighted in a different color corresponding to its node in the hierarchy. Only after the user has reviewed the shifted and duplicated selections in the worksheet and clicked the "accept"



To the table of contents

Supply of Nursing Staff (Trend Variant) in Germany up to 2049, in 1000

Age from ... to under ... Years	Nursing Staff					
	Year	2024	2029	2034	2039	2044
Total	1673	1710	1738	1790	1839	1867
15 - 20	53	55	59	57	57	56
20 - 25	154	152	155	165	160	158
25 - 30	173	174	168	170	181	175
30 - 35	178	186	184	178	180	191
35 - 40	187	192	198	196	190	192
40 - 45	173	201	204	209	207	201
45 - 50	170	190	218	220	226	222
50 - 55	177	177	198	225	228	233
55 - 60	215	177	177	197	225	227
60 - 65	166	170	139	140	156	178
65 - 70	26	36	37	31	31	34
Male	284	304	321	339	356	368
15 - 20	12	13	14	13	13	13
20 - 25	32	32	32	34	33	33
25 - 30	39	40	39	39	41	40
30 - 35	39	43	43	42	42	45
35 - 40	38	42	46	46	44	45
40 - 45	27	35	38	42	42	41
45 - 50	24	26	35	38	41	41
50 - 55	26	25	27	36	39	42
55 - 60	25	25	25	27	35	39
60 - 65	18	18	18	18	19	25
65 - 70	1	1	1	1	1	1
Female	1390	1406	1416	1451	1484	1499

Figure 6: Selection of All Cells in the Subtables by Duplicating the Hierarchy of the First Table

button are the nodes in the hierarchy created as desired. Figure 5 shows the resulting selection after the user approved the

The same method that worked effectively for duplicating the columns can now be applied to the subtables, as shown in Figure 6.

By selecting the node with the value "Total" and clicking the "Move and Duplicate" button, we can apply the selection of the "Total" subtable to the other subtables. This involves shifting the table downward by as many rows as necessary to overlap with the subtable below.

However, there is a minor issue: the child nodes of the "Total" node also include the column headers. If these column headers were repeated in the subtables below, shifting the selections downward would work without modification. Since these cells are not repeated in the subtables, we need to prevent the column headers cells from moving during the duplication process.

To achieve this, we can exclude individual nodes from being moved by locking their selection. This is done by clicking the padlock icon on the corresponding nodes, which freezes their cell selection and keeps them fixed at their original position, regardless of other cells being moved.

Therefore, we identify and select the nodes containing the column headers—specifically, the years 2024 to 2049—and lock their selection using the padlock button. By shifting the selection downward and duplicating it, we can easily move and duplicate the cell selections for the subtables below. By setting the number of repetitions to 2, all subtables are completely selected.

4.4 Path-wise Broadcasting

Figure 7 shows the selection hierarchy that users create on the spreadsheet. For readability, the example restricts itself to the first three columns and rows of the leftmost sub-table.

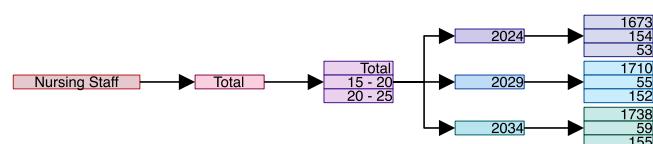


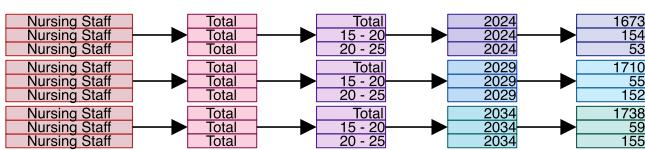
Figure 7: Selection hierarchy before path-wise broadcasting.

697 To produce a flat, relational table, the **SDE** performs *path-wise*
 698 *broadcasting*: for each root-to-leaf path $P = (v_0, \dots, v_k)$ that ends in
 699 a list of N value cells (x_1, \dots, x_N) , the SDE materializes N output
 700 rows by repeating or aligning the labels found along the path.
 701

Concretely:

- 702 (1) **Broadcast singletons.** If a path node carries a single label
 703 (e.g., *Nursing Staff*, *Total*, or a single year), that label is
 704 replicated N times so each value cell inherits it.
- 705 (2) **Align equal-length lists.** If a path node provides a list
 706 of N labels, those labels are paired index-wise with the N
 707 value cells.
- 708 (3) **Emit one tuple per value cell.** For each $j \in \{1, \dots, N\}$,
 709 emit a row that contains the labels gathered from the path
 710 at position j (broadcast or aligned) together with the value
 711 x_j .

712 The resulting hierarchy after broadcasting is illustrated in Figure
 713 8: upstream labels are repeated or aligned so that each numeric
 714 cell is paired with its full context, yielding one relational row per
 715 cell.



722 **Figure 8: Selection hierarchy after path-wise broadcasting.**
 723 Each value cell is paired with its repeated/aligned upstream
 724 context, producing one row per cell.

727 5 Interface Fidelity for Navigation

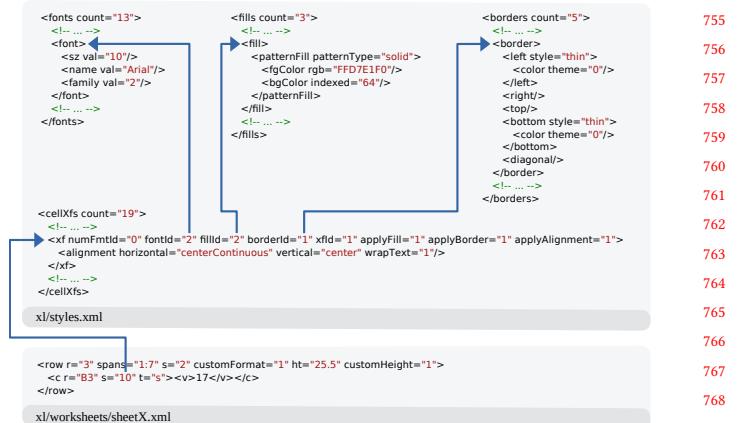
729 To ensure that users can navigate worksheets without difficulty, we
 730 prioritize displaying the worksheets in a manner that closely resembles
 731 their appearance in Excel. This involves accurately rendering
 732 cell dimensions, formatting, and text behaviors.

733 *5.0.1 Displaying Row Heights and Column Widths.* Our solution
 734 extracts information about column widths and row heights directly
 735 from the Excel file's XML structure. Specifically, we retrieve the
 736 column widths from the *width* attribute of the *<col>* elements and
 737 the row heights from the *ht* attribute of the *<row>* elements in the
 738 *sheetX.xml* files.

739 In Excel, column widths and row heights are defined in units
 740 that do not directly correspond to pixels, requiring conversion for
 741 precise on-screen rendering. Moreover, different scaling factors are
 742 applied for columns and rows. Despite extensive research, we were
 743 unable to find official documentation that explains the rationale
 744 behind these specific scaling factors. Based on empirical testing,
 745 we derived the following scaling factors:

- 747 • **Column Widths:** Multiply the *width* attribute by 7.
- 748 • **Row Heights:** Multiply the *ht* attribute by $\frac{4}{3}$.

749 *5.0.2 Cell Formatting.* Cell formatting plays a crucial role in ac-
 750 curately representing the appearance of worksheets. Formatting
 751 information is stored in the *styles.xml* file, where styles are de-
 752 fined and later referenced in the *sheetX.xml* files as shown in
 753 Figure 9.



755 **Figure 9: Illustration of the relationship between style def-
 756 initions in *xl/styles.xml* (fonts, fills, borders, and *cellXfs*)
 757 and their application in a worksheet file (*xl/worksheets/
 758 sheetX.xml*).**

759 Each cell in the worksheet references a style index through the *s*
 760 attribute, which points to the corresponding *<xf>* element within
 761 the *cellXfs* collection. These *<xf>* elements contain attributes
 762 such as *fontId*, *fillId*, and *borderId*, which reference specific font,
 763 fill (background), and border definitions located in the *fonts*, *fills*,
 764 and *borders* collections, respectively. By parsing these references,
 765 we can accurately apply the appropriate fonts, background colors,
 766 and border styles to each cell.

767 Through meticulous parsing and application of these formatting
 768 details, we ensure that the rendered worksheet closely mirrors the
 769 original Excel file, preserving the visual cues and aesthetics that
 770 users expect.

771 *5.0.3 Handling Text Overflow.* In Excel, when the content of a cell
 772 exceeds its width, the text may overflow into adjacent empty cells,
 773 provided those cells do not contain any data. If adjacent cells are
 774 occupied, Excel truncates the overflowing text at the cell boundary.
 775 Replicating this behavior is essential for accurate rendering and
 776 user familiarity.

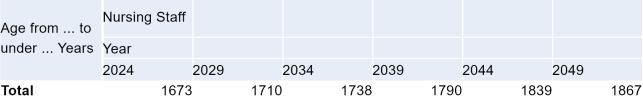
777 We implemented text overflow handling by checking if the ad-
 778 jacent cell to the right is empty before allowing text to overflow.
 779 If the adjacent cell is empty, we extend the text rendering. If the
 780 adjacent cell contains data, we truncate the text at the boundary of
 781 the original cell.

782 Figure 1 illustrates this behavior. The text "Supply of Nursing
 783 Staff ..." extends into the neighboring cell because it is empty. If not
 784 for this handling, the text would be truncated at the cell boundary,
 785 leading to incomplete data display as shown in Figure 10.

786 By accurately handling text overflow, we improve readability and
 787 maintain consistency with Excel's user interface, which is crucial
 788 for users transitioning between Excel and our tool.

807 6 Scalable Parsing, Indexing, and Rendering

808 This section describes how the SDE achieves interactive perfor-
 809 mance on large or bloated worksheets: (i) *incremental loading* of
 810 XLSX assets, (ii) a *byte-level worksheet parser* that avoids DOMs and

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822	Figure 10: Incorrect rendering without overflow for cells adjacent to empty cells.
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826	regex, (iii) compact indexes for merged regions and column geometry, (iv) <i>on-demand</i> streaming of rows and cells, and (v) <i>viewport-bounded</i> rendering.
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830	<h2>6.1 Incremental Loading of Worksheets</h2>
831	Opening large Excel files traditionally involves loading the entire file and all its worksheets into memory before displaying any content. In files containing very large worksheets, this process can take several seconds to minutes, causing significant delays for users who need to access data quickly.
832	
833	To facilitate efficient data extraction from multiple Excel files, we implemented a mechanism for incremental loading of worksheets within the SDE. Excel files (.xlsx format) are ZIP archives containing a collection of XML files that describe the worksheets, styles, and shared strings. Key components include:
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842	<ul style="list-style-type: none">• xl/sharedStrings.xml: Contains all the unique strings used across worksheets, reducing redundancy.• xl/styles.xml: Defines the formatting styles for cells, including fonts, colors, and borders.• xl/worksheets/sheetX.xml: Represents individual worksheets (sheet1.xml, sheet2.xml, etc.).
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849	Our solution opens the Excel file as a ZIP archive and initially extracts only the essential metadata and shared resources required for the application to function. This initial extraction includes:
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852	(1) Metadata Extraction :
853	We read the archive's directory to identify the contained files without decompressing them fully. This step is quick, taking only a few milliseconds, and provides information about the available worksheets and shared resources.
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857	(2) Selective Extraction :
858	We immediately extract <code>sharedStrings.xml</code> and <code>styles.xml</code> because these files are small and contain information necessary for rendering cell content and styles across all worksheets. These files are parsed and stored in memory for quick access during rendering.
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863	(3) Deferred Worksheet Loading : The individual worksheet files (<code>sheetX.xml</code>) remain compressed and are loaded into memory in their binary unextracted form. They are not decompressed or parsed at this stage.
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867	(4) On-Demand Parsing :
868	When a user accesses a specific worksheet—either by selecting it in the interface or when a unit test requires data
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from it—the corresponding `sheetX.xml` file is then decompressed and parsed. This parsing occurs in the background and is triggered only by direct user action or programmatic access to the worksheet's data.

(5) **Memory Release**:

After a worksheet has been decompressed and its XML parsed, we release the memory resources associated with the parsed data. This approach prevents excessive memory usage and ensures that the application remains responsive even when working with multiple large worksheets.

By adopting this incremental loading approach, users experience minimal wait times when opening an Excel file. The initial loading is nearly instantaneous, allowing users to begin interacting with the application without delay. This contrasts with traditional methods that require loading all worksheets upfront, leading to significant wait times for large files.

6.2 Parsing Worksheet XML with Byte-Level Pattern Matching

DOM-based parsers and regex-on-strings do not scale for very large worksheets: they require full decoding to UTF-16/UTF-8 and materialize enormous trees. In Dart, regular expressions cannot operate on byte arrays, so converting a gigabyte-scale `Uint8List` to a string alone can cost seconds. The SDE therefore parses *directly on bytes*, matching ASCII tag sentinels and reading attributes in place, decoding strings only on demand.

Parsing roadmap. Excel worksheets expose a stable top-level order: `<sheetFormatPr>`, `<cols>`, `<sheetData>`, `<mergeCells>`. We first anchor the end of `<sheetData>` by a backward byte search (Alg. 1); then we parse metadata around it:

- `<mergeCells>` (after `</sheetData>`),
- `<sheetFormatPr>` (before `<sheetData>`) and
- `<cols>` (before `<sheetData>`)

and enter *sheet-data mode* only when rows or cells are actually needed.

Anchoring & metadata. We find the closing sentinel `</sheetData>` by scanning backward and validating the 12-byte pattern (Alg. 1). This yields byte indices that bound all subsequent searches and lets us enumerate `<mergeCell ... ref="A1:B3">` elements linearly, converting each A1 pair to (r, c) and inserting the span into a compact index with binary-search probes and a prefix-maximum (used later by `spanAt`, Alg. 4).

Defaults and column bands. We record the default row height H_d (attribute `defaultRowHeight`) and the default column width W_d (attribute `defaultColWidth`) in the `<sheetFormatPr ...>` node. From `<cols>` we parse each element of the form `<col min="i" max="j" width="w">`, which defines a *column band* $[i:j]$ with width w . Bands are stored in ascending order of \min ; queries such as retrieving the width at column c or the column at a given horizontal offset are answered via a linear or $O(\log B)$ search over these bands.

Streaming rows and accumulating offsets. Entering sheet-data mode, we stream `<row ...>` tags without decoding payloads. Within each opening tag we read `r="..."` (row index) and optional `ht="..."` (height). For each discovered row we cache its byte interval and

Algorithm 1: Backward search for </sheetData>

```

Input:  $b$ : bytes;  $[lo, hi]$ : search window
Output:  $sheetDataCloseByte$  or  $-1$ 
Function  $FindSheetDataEndBackward(b, lo, hi)$ :
     $pat \leftarrow$  bytes of </sheetData>
     $m \leftarrow |pat|$ 
    for  $i \leftarrow hi - m$  downto  $lo$  do
        if  $b[i] = pat[0]$  and  $b[i + m - 1] = pat[m - 1]$  and
            EqualAt( $b, i, pat$ ) then
                return  $i$ 
    return  $-1$ 

```

compute its top offset incrementally using explicit heights or the default H_d :

$$\text{off}_1 = (r_1 - 1) H_d, \quad \text{off}_i = \text{off}_{i-1} + (h_{i-1} \text{ or } H_d) + (r_i - r_{i-1} - 1) H_d.$$

See Alg. 2.

Lazy cell parsing. Given a row byte interval $[s, e]$, cells are parsed on demand. We scan for <c, read attributes ($r="A123"$, $s="..."$, $t="..."$), and bound the cell interval by the next <c or the row end. Values are extracted *within* this interval from <v>...</v> or (for inline strings) <is>...</is>. See Alg. 3. Because Excel enforces increasing row indices, we can stop row streaming as soon as we pass the requested row.

Merged regions. Merged areas are rectangles $[r_1, r_2] \times [c_1, c_2]$. We normalize and sort spans by (r_1, c_1) , store parallel arrays R_1, C_1, R_2, C_2 , and build a prefix-maximum PM over R_2 . A point query $\text{spanAt}(r, c)$ uses (i) a binary search on R_1 to cap candidates above r , (ii) a binary search over PM to drop candidates ending before r , (iii) a binary search on C_1 to find those with $c_1 \leq c$, then a short local check; an origin map answers “is this cell the origin?” in $O(1)$. See Alg. 4.

Scroll extents (without decoding payloads). We obtain r_{\max} by scanning backward to the last <row ... r="...">. A single forward pass accumulates $\sum_{r \in E} \text{ht}(r)$ and counts $|E|$; all other rows use H_d . In device units,

$$H_{\text{sheet}} = \sum_{r \in E} \text{ht}(r) + (r_{\max} - |E|) H_d.$$

Horizontally, letting c_{\max} be the largest covered column,

$$W_{\text{sheet}} = \text{colOff}(c_{\max}) + w(c_{\max}).$$

These extents parameterize the viewport and drive scrollbar sizing in the UI.

Complexity and memory. All searches are bounded by structural sentinels (>, next <row, next <c, or </sheetData>). Anchoring </sheetData> is $O(N)$ with tiny constants; row streaming is $O(R)$ with $O(1)$ per-row offset updates; a targeted cell within a row scans only that row’s interval; merge queries run in $O(\log M + \alpha)$ with a short local scan α . The representation is compact (byte slices + small numeric state), and strings are decoded only when needed.

6.3 Two-Dimensional Grid Viewport Rendering

Given a (potentially very large) worksheet with variable row heights, banded column widths, and merged regions, we lay out only tiles intersecting the current viewport. The renderer works in device pixels but derives all positions from the byte-level parser. Our goal

Algorithm 2: Stream rows & compute offsets

```

Input:  $b$ : bytes; window  $[o, c)$  with  $o =$  index after <sheetData...>,  $c =$  index of </sheetData>; default height  $H_d$ ; pixel scale  $\rho$ 
Output: sequence of  $(r, [s, e], h, off)$ 
Function  $RowsWithOffsets(b, [o, c), H_d, \rho)$ :
     $i \leftarrow o$ ;  $\text{prevR} \leftarrow \perp$ ;  $\text{prevH} \leftarrow \perp$ ;  $\text{prevOff} \leftarrow 0$ ;  $\text{prevS} \leftarrow \perp$ 
    while  $i \leq c - 4$  do
        if  $b[i..i+3] = <\text{row}>$  then
             $s \leftarrow i$ 
             $(r, h, j) \leftarrow \text{PARSEROWATTRS}(b, i, c)$  // advances to just after >
            if  $\text{prevR} = \perp$  then
                 $\text{off} \leftarrow \rho \cdot (r - 1) H_d$ 
            else
                 $g \leftarrow r - \text{prevR} - 1$ 
                 $H_{\text{prev}} \leftarrow (\text{prevH or } H_d)$ 
                 $\text{off} \leftarrow \text{prevOff} + \rho \cdot H_{\text{prev}} + \rho \cdot g H_d$ 
            if  $\text{prevR} \neq \perp$  then emit  $\langle \text{prevR}, [\text{prevS}, s), \text{prevH}, \text{prevOff} \rangle$ 
             $\text{prevR} \leftarrow r$ ;  $\text{prevH} \leftarrow h$ ;  $\text{prevOff} \leftarrow \text{off}$ ;  $\text{prevS} \leftarrow s$ 
             $i \leftarrow j$ 
        else
             $i \leftarrow i + 1$ 
    if  $\text{prevR} \neq \perp$  then emit  $\langle \text{prevR}, [\text{prevS}, c), \text{prevH}, \text{prevOff} \rangle$ 

```

Input: b : bytes; i : index at <row>; c : close bound (sheet end)
Output: (r, h, j) : row index r (or \perp), optional height h (or \perp), and j = first byte after >

```

Function  $\text{ParseRowAttrs}(b, i, c)$ :
     $r \leftarrow \perp$ ;  $h \leftarrow \perp$ ;  $j \leftarrow i + 4$ 
    while  $j < c$  do
        if  $b[j] = >$  then
             $j \leftarrow j + 1$ ; return  $(r, h, j)$ 
        if  $b[j] = r$  and  $b[j - 1]$  is space then
             $k \leftarrow j + 1$ 
             $(s, e) \leftarrow \text{GETINNERATTRINTERVAL}(k, c, b)$ 
            if  $(s, e) \neq \perp$  then  $r \leftarrow \text{PARSEINTASCII}(b, s, e)$ 
        if  $b[j..j + 1] = ht$  and  $b[j - 1]$  is space then
             $k \leftarrow j + 2$ 
             $(s, e) \leftarrow \text{GETINNERATTRINTERVAL}(k, c, b)$ 
            if  $(s, e) \neq \perp$  then  $h \leftarrow \text{PARSEDOUBLEASCII}(b, s, e)$ 
         $j \leftarrow j + 1$ 
    return  $(r, h, j)$  // malformed tail safely falls through

```

Input: i : scan index after the attribute name; n : hard bound; b : bytes
Output: (s, e) inner half-open interval, or \perp if not well-formed

```

Function  $\text{GetInnerAttrInterval}(i, n, b)$ :
    while  $i < n$  and  $b[i]$  is space do
         $i \leftarrow i + 1$ 
    if  $i < n$  and  $b[i] ==$  then
         $i \leftarrow i + 1$ 
        while  $i < n$  and  $b[i]$  is space do
             $i \leftarrow i + 1$ 
        if  $i < n$  and  $(b[i] = " or b[i] = ')$  then
             $q \leftarrow b[i]; i \leftarrow i + 1; s \leftarrow i$ 
            while  $i < n$  and  $b[i] \neq q$  do
                 $i \leftarrow i + 1$ 
            return  $(s, i)$ 
    return  $\perp$ 

```

is *frame-local* work proportional to the number of *visible* rows/columns, independent of sheet size. Algorithm 4 summarizes the procedure. Throughout, index intervals are half-open $[a, b)$.

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Algorithm 3: Resolve cell (r, c) by streaming the row

```

1045 Input:  $b$ : bytes; row interval  $[S, E)$ ; target column  $c$ 
1046 Output: cell interval  $[s, e)$  or  $\perp$ 
1047  $i \leftarrow S$ 
1048 while  $i \leq E - 2$  do
1049   if  $b[i..i+1] = <c$  then
1050      $s \leftarrow i$ 
1051      $(c', j) \leftarrow \text{PARSECELLCOL}(b, i, E)$  // reads r="A123" and
1052       advances to just after >
1053       // end of this cell = next <c or E
1054        $k \leftarrow j$ 
1055       while  $k \leq E - 2$  and  $b[k..k+1] \neq <c$  do
1056          $\quad k \leftarrow k + 1$ 
1057          $e \leftarrow (k \leq E - 2) ? k : E$ 
1058         if  $c' = c$  then
1059            $\quad \text{return } [s, e)$ 
1060          $i \leftarrow e$ 
1061       else
1062          $\quad i \leftarrow i + 1$ 
1063
1064   return  $\perp$ 

```

Inputs. Let x_0, y_0 be the horizontal/vertical scroll offsets (device pixels) and W_{vp}, H_{vp} the viewport size. We use a small *cache extent* $\Delta > 0$ to pre-build tiles that will imminently enter view, rendering over $[x_0, x_0 + W_{vp} + \Delta] \times [y_0, y_0 + H_{vp} + \Delta]$. Row geometry comes from the streaming parser: each row r has a top offset $\text{off}(r)$ and a height $h(r)$ (explicit ht if present, otherwise the default). Columns are given as ordered bands; for column c we can query its width $w(c)$ and cumulative offset $\text{colOff}(c)$. Merged regions are indexed by a structure that decides, in logarithmic time, whether a coordinate (r, c) is covered and, if so, by which span.

Visible set. We invert the cumulative-height/width functions:

$$\begin{aligned} r_\ell &= \lfloor \text{rowIndexAt}(y_0) \rfloor, & r_u &= \lceil \text{rowIndexAt}(y_0 + H_{vp} + \Delta) \rceil, \\ c_\ell &= \lfloor \text{colIndexAt}(x_0) \rfloor, & c_u &= \lceil \text{colIndexAt}(x_0 + W_{vp} + \Delta) \rceil. \end{aligned}$$

Here $\text{rowIndexAt}(y)$ and $\text{colIndexAt}(x)$ are binary searches over cumulative extents built from parsed row heights and column bands, yielding $O(\log R)$ and $O(\log B)$ lookup time, respectively.

Cell coordinates and merge spans. A merged region is a closed rectangle $[r_1, r_2] \times [c_1, c_2]$ with $r_1 \leq r_2$ and $c_1 \leq c_2$. We sort spans by origin (r_1, c_1) and materialize parallel arrays R_1, C_1, R_2, C_2 plus a prefix-maximum array $\text{PM}[i] = \max_{0 \leq j \leq i} R_2[j]$. An origin map supports $O(1)$ checks that (r, c) is the top-left of a span. Membership “is (r, c) covered?” runs in three bounded steps:

- (1) **Row window (binary search).** $hi = \text{ub}(R_1, r)$; candidates lie in $[0, hi]$. Then $lo = \text{lb}(\text{PM}[0:hi], r)$ discards all indices with $R_2 < r$.
- (2) **Column narrowing (binary search).** $k = \text{ub}(C_1[lo:hi], c) - 1$ is the last origin with $c_1 \leq c$.
- (3) **Local check (constant expected).** Scan left from k while $C_1[i] \leq c$; accept if $r \leq R_2[i]$ and $c \leq C_2[i]$.

We use $\text{ub}(A, x) = \min\{i \mid A[i] > x\}$ and $\text{lb}(A, x) = \min\{i \mid A[i] \geq x\}$. This yields $O(\log M + \alpha)$ time, where α is a short local scan in practice.

Origin-first placement for merged regions. A naïve scan of $[r_\ell:r_u] \times [c_\ell:c_u]$ would instantiate merged tiles multiple times. Instead, we

pre-place only spans whose origins lie outside the leading edges but whose rectangles intersect the viewport: probe the top border $(r_\ell, c_\ell:c_u)$ and the left border $(r_\ell:r_u, c_\ell)$, query $\text{spanAt}(r, c)$, and place the tile once at its origin (r_s, c_s) . We maintain a burned set B to avoid duplicates in the interior.

Interior tiling. Traverse the visible grid and place a tile at (r, c) only if (i) no span covers it, or (ii) (r, c) is the origin of its span (checked in $O(1)$). Device positions are $x = \text{colOff}(c) - x_0$, $y = \text{off}(r) - y_0$.

Scroll extents. We size the vertical scroll domain from row attributes without decoding payloads. Anchored at $</sheetData>$, we scan backward to the last $<\text{row} \dots>$ to read r_{\max} from $r=" \dots "$. A single forward pass accumulates explicit heights $\sum_{r \in E} \text{ht}(r)$ and counts them as $|E|$; all other rows in $1..r_{\max}$ use the default H_d . With device pixels,

$$H_{\text{sheet}} = \sum_{r \in E} \text{ht}(r) + (r_{\max} - |E|) H_d.$$

Horizontally, with c_{\max} the highest covered column,

$$W_{\text{sheet}} = \text{colOff}(c_{\max}) + w(c_{\max}).$$

These extents parameterize the viewport and drive scrollbar sizing/positioning (*two-dimensional scrollables* [13]).

Correctness and complexity. Edge probes ensure any merged region intersecting the viewport but originating above/left is instantiated *exactly once* at its origin. The interior pass either places unmerged cells or the unique origin cell of each merged region. Let $R_{\text{vis}} = r_u - r_\ell + 1$ and $C_{\text{vis}} = c_u - c_\ell + 1$. Passes 1–2 cost $O(R_{\text{vis}} + C_{\text{vis}})$; Pass 3 costs $O(R_{\text{vis}} C_{\text{vis}})$ and does no work outside the visible rectangle. The burned set is updated at most once per span per frame.

6.4 AABB-Indexed Selection Lookup

Each selection source (a task or composed group) maintains a lazily computed, cached *axis-aligned bounding box* (AABB) that is invalidated on updates and recomputed on demand. When many such selection sources (grids) intersect the viewport, a linear scan over their bounding boxes can dominate latency. We therefore maintain a lightweight index over axis-aligned bounding boxes (AABBs) to answer point queries (x, y) in $O(\log G + \alpha)$ time, where G is the number of visible grids and α is the size of a narrow candidate window.

Each grid i exposes a bounding rectangle $[L_i, R_i] \times [T_i, B_i]$ in grid coordinates and a point predicate $\text{findCell}_i(x, y)$ that returns the cell at (x, y) or \perp . We build parallel arrays L, R, T, B (left, right, top, bottom) and a stable original-order index O (used to break ties consistently with the UI). Let σ be the permutation that sorts grids by nondecreasing T (top edge). In that order we form a prefix-maximum array $\text{PM}[j] = \max_{0 \leq i \leq j} B_{\sigma(i)}$. For a query row y , the candidate window is the tightest interval $[\ell, h]$ such that all boxes whose top $\leq y$ and bottom $\geq y$ lie in that interval; we obtain $h = \text{ub}(T_\sigma, y)$ and $\ell = \text{lb}(\text{PM}[0:h], y)$ by binary search (ub: strict upper bound; lb: lower bound). We then prune by the x -interval condition $L \leq x \leq R$. Among the surviving candidates we test findCell in increasing O (original) order and return the first hit; if none match, the answer is \perp .

Algorithm 4: Viewport layout with merge-aware origin-first placement

```

1161 Input:  $x_0, y_0; W_{vp}, H_{vp}$ ; cache  $\Delta$ ; sheet accessories
1162           rowIndexAt, colIndexAt, off, colOff,  $h, w$ ; merge index
1163           spanAt, isOrigin
1164
1165   Output: positioned tiles for current frame
1166   // Visible indices
1167    $r_\ell \leftarrow \lfloor \text{rowIndexAt}(y_0) \rfloor, r_u \leftarrow \lceil \text{rowIndexAt}(y_0 + H_{vp} + \Delta) \rceil$ 
1168    $c_\ell \leftarrow \lfloor \text{colIndexAt}(x_0) \rfloor, c_u \leftarrow \lceil \text{colIndexAt}(x_0 + W_{vp} + \Delta) \rceil$ 
1169    $B \leftarrow \emptyset$  // burned merged spans
1170
1171   // Pass 1: top border probes
1172   for  $c \leftarrow c_\ell$  to  $c_u$  do
1173      $S \leftarrow \text{spanAt}(r_\ell, c)$ 
1174     if  $S \neq \perp$  and  $S \notin B$  and  $r_S < r_\ell$  then
1175       place tile for  $S$  at  $(\text{colOff}(c_S) - x_0, \text{off}(r_S) - y_0)$ 
1176        $B \leftarrow B \cup \{S\}$ 
1177
1178   // Pass 2: left border probes
1179   for  $r \leftarrow r_\ell$  to  $r_u$  do
1180      $S \leftarrow \text{spanAt}(r, c_\ell)$ 
1181     if  $S \neq \perp$  and  $S \notin B$  and  $c_S < c_\ell$  then
1182       place tile for  $S$  at  $(\text{colOff}(c_S) - x_0, \text{off}(r_S) - y_0)$ 
1183        $B \leftarrow B \cup \{S\}$ 
1184
1185   // Pass 3: interior tiles
1186   for  $c \leftarrow c_\ell$  to  $c_u$  do
1187      $x \leftarrow \text{colOff}(c) - x_0$ 
1188     for  $r \leftarrow r_\ell$  to  $r_u$  do
1189        $y \leftarrow \text{off}(r) - y_0$ 
1190        $S \leftarrow \text{spanAt}(r, c)$ 
1191       if  $S = \perp$  or  $\text{isOrigin}(S, (r, c))$  then
1192         place tile at  $(x, y)$ 
1193
1194   //  $\text{ub}(A, x) = \min\{i \mid A[i] > x\}$ ,  $\text{lb}(A, x) = \min\{i \mid A[i] \geq x\}$ .
1195   Function  $\text{spanAt}(r, c)$ :
1196      $hi \leftarrow \text{ub}(R_1, r)$ 
1197     if  $hi = 0$  then
1198        $\perp$ 
1199      $lo \leftarrow \text{lb}(\text{PM}[0:hi], r)$ 
1200     if  $lo \geq hi$  then
1201        $\perp$ 
1202      $k \leftarrow \text{ub}(C_1[lo:hi], c) - 1$ 
1203     if  $k < lo$  then
1204        $\perp$ 
1205     for  $i \leftarrow k$  downto  $lo$  do
1206       if  $C_1[i] > c$  then
1207          $\perp$ 
1208       if  $r \leq R_2[i]$  and  $c \leq C_2[i]$  then
1209          $\text{span } i$ 
1210
1211    $\perp$ 

```

The index builds in $O(G \log G)$ time and consists of six integer arrays plus the permutation π . It is invalidated on any structural change to the set of grids (move, resize, insert/delete) and rebuilt lazily on the next query. For small G (e.g., $G \leq 32$) we fall back to a linear scan; the cutover can be tuned empirically.

6.5 Lazy Output Flattening and Row Location

Large workbooks and selection hierarchies make fully materializing a relational view prohibitively expensive. Empirically, naive flattening leads to seconds or minutes of UI stalls on sheets with up to 10^6 rows (Excel's limit) and many columns. Our goal is to *render only what the user is about to see*, without precomputing the entire output.

Algorithm 5: AABB-indexed selection lookup over visible grids

```

1219 Input: point  $(x, y)$ ; arrays  $L, R, T, B$ ; permutation  $\sigma$  sorting by  $T$ ; prefix max
1220           PM over  $B_{\sigma(\cdot)}$ ; original-order  $O$ ; accessor  $\text{findCell}_i(x, y)$ 
1221
1222   Output: either  $\langle i, \text{cell} \rangle$  or  $\perp$ 
1223   // Binary-search helpers:  $\text{ub}(A, z) = \min\{i \mid A[i] > z\}$ ,
1224            $\text{lb}(A, z) = \min\{i \mid A[i] \geq z\}$ .
1225
1226   // 1) Y-narrowing: window of candidates whose top  $\leq y$  and
1227           bottom  $\geq y$ 
1228    $h \leftarrow \text{ub}(T_\sigma, y)$  // first index with  $T_{\sigma(h)} > y$ 
1229   if  $h = 0$  then
1230      $\perp$ 
1231    $\ell \leftarrow \text{lb}(\text{PM}[0:h], y)$  // first prefix with bottom  $\geq y$ 
1232   if  $\ell \geq h$  then
1233      $\perp$ 
1234
1235   // 2) X-pruning: keep only boxes covering  $x$ 
1236    $C \leftarrow \emptyset$ 
1237   for  $j \leftarrow \ell$  to  $h - 1$  do
1238      $i \leftarrow \sigma(j)$ 
1239     if  $L_i \leq x \leq R_i$  then
1240       append  $i$  to  $C$ 
1241
1242   if  $C = \emptyset$  then
1243      $\perp$ 
1244
1245   // 3) Stable tie-break and confirmation
1246    $C \leftarrow \text{sort } C$  by increasing  $O_i$  // preserve UI order/colors
1247   foreach  $i \in C$  do
1248      $\text{ans} \leftarrow \text{findCell}_i(x, y)$ 
1249     if  $\text{ans} \neq \perp$  then
1250        $\perp$ 
1251
1252   return  $\langle i, \text{ans} \rangle$ 
1253
1254    $\perp$ 

```

Design overview. We model the visible table as a single *global row space* obtained by concatenating many small, contiguous *row blocks*. Each block is produced by streaming the hierarchy files \rightarrow tasks \rightarrow sheets \rightarrow cellTasks in a deterministic order. The UI asks for a particular global row index r (e.g., the first row currently in the viewport); we then extend the stream just far enough so that r falls inside a cached block. This *on-demand flattening* avoids touching unrelated parts of the hierarchy.

Data structures. We maintain two parallel arrays: (i) *blocks* contains the realized row blocks (each stores *startRow*, *len*, *path*, *cells*, and the active workbook/sheet), and (ii) *starts* stores the corresponding *startRow* values. By construction, *starts* is strictly increasing. A FIFO queue Q holds pending (*task*, *path*) frames for a breadth-first streaming traversal. Traversal indices over files/sheets/tasks/sheets maintain the current context (*activeWb*, *activeSheet*). Optional caps B_{\max} and R_{\max} bound memory by pruning the oldest blocks.

Driver and lookup. When the UI requests row r , *ENSUREBUILT-THROUGHROW* extends the stream until $\text{builtRows} > r$ or the source is exhausted (Alg. 6). We then locate the block via a binary search over *starts* (*upper bound* on r and step one back), yielding the block index and the local in-block offset (Alg. 6, *LOCATEROW*). Both steps are $O(k)$ work to extend by k newly discovered rows plus $O(\log |\text{starts}|)$ for the lookup.

Streaming next block. *NEXTBLOCK* (Alg. 7) emits the next contiguous block. If Q is empty we call *FILLQUEUEIFEMPTY* to advance to the next *source segment* (file, sheet task, sheet pair) with non-empty roots. Otherwise we pop a frame. If the popped task has no

Algorithm 6: Lazy row locator: driver and lookup (part A)

```

1277 Input: hierarchy files → tasks → sheets → cellTasks; caps  $B_{\max}, R_{\max}$ 
1278 Output: on demand: for global row  $r$ , return (RowBlock, local) or  $\perp$ 
1279 State: arrays  $blocks, starts$ ; queue  $Q$ ; indices  $fi, sti, si$ ;  $curFile, curTask$ ;
1280  $curSheets$ ; ( $activeWb, activeSheet$ )
1281 Function EnsureBuiltThroughRow( $r$ ):
1282   while  $builtRows \leq r$  do
1283      $rb \leftarrow NextBlock()$ 
1284     if  $rb = \perp$  then
1285       break
1286     append  $rb$  to  $blocks$ ; append  $rb.startRow$  to  $starts$ ;
1287     PruneHeadIfNeeded()
1288
1289 Function LocateRow( $r$ ):
1290   EnsureBuiltThroughRow( $r$ )
1291   if  $blocks = \emptyset$  then
1292     return  $\perp$ 
1293    $lo \leftarrow 0$ ;  $hi \leftarrow |starts|$ 
1294   while  $lo < hi$  do
1295      $mid \leftarrow \lfloor (lo + hi)/2 \rfloor$ 
1296     if  $starts[mid] \leq r$  then
1297        $lo \leftarrow mid + 1$ 
1298     else
1299        $hi \leftarrow mid$ 
1300
1301      $idx \leftarrow lo - 1$ 
1302     if  $idx < 0$  then
1303       return  $\perp$ 
1304      $b \leftarrow blocks[idx]$ ;  $local \leftarrow r - b.startRow$ 
1305     if  $0 \leq local < b.len$  then
1306       return  $(b, local)$ 
1307     else
1308       return  $\perp$ 
1309

```

children, its `sortedSelectedCells` form a new RowBlock (start = `builtRows`, length = number of selected cells) and we return it. If the task has children, we enqueue each child with the extended path. This BFS over the selection tree yields a deterministic, top-down order that matches the user's mental model.

Algorithm 7: Row block generation (part B): NEXTBLOCK

```

1310 Function NEXTBLOCK:
1311   if  $\neg FillQueueIsEmpty()$  then
1312     return  $\perp$ 
1313   while true do
1314     if  $Q = \emptyset$  then
1315       if  $\neg FillQueueIsEmpty()$  then
1316         return  $\perp$ 
1317       continue
1318      $(t, path) \leftarrow pop-front Q$ 
1319     if  $t.children = \emptyset$  then
1320        $cells \leftarrow t.sortedSelectedCells$ 
1321       if  $|cells| = 0$  then
1322         continue
1323        $start \leftarrow builtRows$ ;  $len \leftarrow |cells|$ 
1324       return
1325        $RowBlock(activeWb, activeSheet, path, cells, start, len)$ 
1326      $nextPath \leftarrow path \cup \{t\}$ 
1327     foreach  $u \in t.children$  do
1328       push-back  $(u, nextPath)$  into  $Q$ 

```

Source advancement. `FILLQUEUEIFEMPTY` (Alg. 8) advances through the outer hierarchy: it steps files (fi), sheet tasks (sti), then sheet pairs (si). For each sheet pair (wb, sh) it materializes the roots (`importExcelCellsTasks`) into Q and sets the active context used to form RowBlocks. If a segment has no roots, it is skipped. When

the last file is exhausted and Q remains empty, the function returns **false** and the stream is complete.

Algorithm 8: Traversal feeding (part C): FILLQUEUEIFEMPTY

```

1335 Function FILLQUEUEIFEMPTY:
1336   while  $Q = \emptyset$  do
1337     if  $curTask = \perp$  then
1338       if  $fi \geq |files|$  then
1339         return false
1340        $curFile \leftarrow files[fi + 1]$ ;  $sti \leftarrow 0$ 
1341
1342       if  $sti \geq |curFile.sheetTasks|$  then
1343          $curTask \leftarrow \perp$ ; continue
1344
1345        $curTask \leftarrow curFile.sheetTasks[sti + 1]$ ;  $curSheets \leftarrow$ 
1346       list( $curTask.sheets$ );  $si \leftarrow 0$ 
1347
1348       while  $si < |curSheets|$  and  $Q = \emptyset$  do
1349          $(wb, sh) \leftarrow curSheets[si + 1]$ ;
1350          $roots \leftarrow curTask.importExcelCellsTasks$ 
1351         if  $|roots| = 0$  then
1352           continue
1353          $Q \leftarrow$  queue of  $(root, \emptyset)$  for each  $root \in roots$ 
1354          $activeWb \leftarrow wb$ ;  $activeSheet \leftarrow sh$ 
1355
1356       if  $Q \neq \emptyset$  then
1357         return true
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```

Cache pruning. `PRUNEHEADIFNEEDED` (Alg. 9) trims the front of the cache to respect either (i) a block count cap B_{\max} , or (ii) a total cached row cap R_{\max} . Trimming removes the oldest blocks and their starts while preserving the invariant that `starts` remains strictly increasing and aligned with `blocks`. In practice we choose small caps that comfortably cover one or two viewport heights plus prefetch.

Algorithm 9: Cache pruning (part D): PRUNEHEADIFNEEDED

```

1368 Function PRUNEHEADIFNEEDED:
1369    $rm \leftarrow 0$ 
1370   if  $B_{\max} \neq \perp$  and  $|blocks| > B_{\max}$  then
1371      $rm \leftarrow |blocks| - B_{\max}$ 
1372   if  $R_{\max} \neq \perp$  then
1373     while  $rm < |blocks|$  do
1374        $cached \leftarrow blocks[|blocks| - 1].startRow +$ 
1375        $blocks[|blocks| - 1].len - blocks[0].startRow$ 
1376       if  $cached \leq R_{\max}$  then
1377         break
1378        $rm \leftarrow rm + 1$ 
1379
1380
1381
1382
1383
1384
1385
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```

Invariants and correctness. (1) **Monotone coverage:** every emitted block has `startRow = builtRows` at creation time, and we update `builtRows ← builtRows + len`; thus blocks are disjoint and cover $[0, builtRows]$ without gaps. (2) **Sorted index:** `starts` is strictly increasing; binary search always returns the last block whose `start ≤ r`. (3) **Determinism:** the traversal order is completely determined by the order of files/sheet-tasks/sheets and by the top-down BFS over the selection tree; repeated runs produce identical global row layouts. (4) **Progress:** each child is enqueued at most once and each leaf produces at most one block; the stream terminates after a bounded number of steps.

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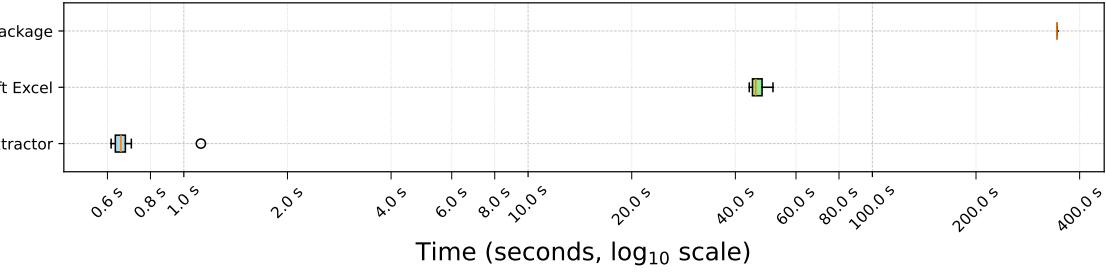
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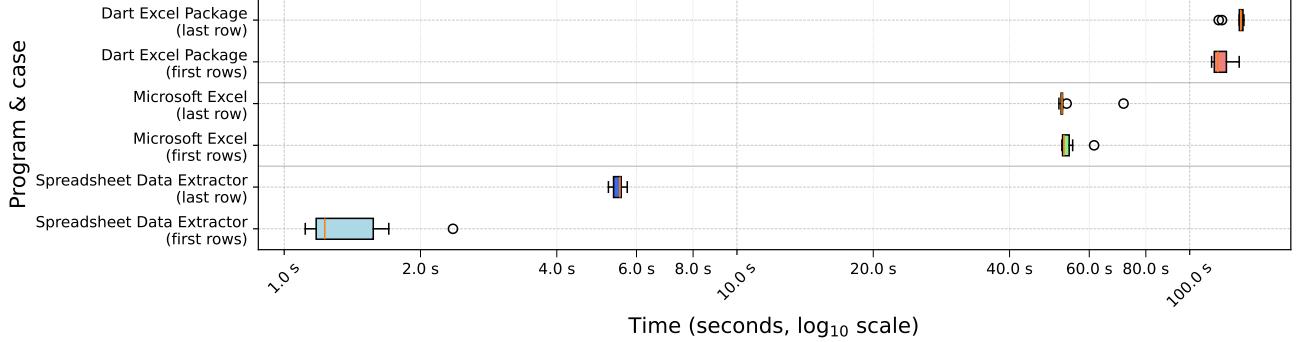
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Comparison of Execution Times for Opening One Excel Sheet



(a) Large multi-worksheet workbook: opening one selected sheet (user-centred latency).

Execution Times: First vs Last Row of Large Worksheet (Grouped by Program)



(b) Single-worksheet benchmark (1,048,548 rows): first vs. last row per programme.

Figure 11: Time-to-first-visual vs. full-parse costs across tools. (a) shows the practical benefit of initialising only the selected sheet in a multi-worksheet file; (b) isolates algorithmic differences under identical workload. Both plots aggregate 10 runs on a \log_{10} time axis.

Complexity. Let N be the number of leaf tasks that produce non-empty `sortedSelectedCells`s, and let $M = \sum \text{len}$ be the total number of output rows. Streaming is linear in the explored work: each internal node is visited once and each leaf contributes $O(1)$ metadata plus $O(\text{len})$ to copy/select references to its cells. A lookup for row r costs $O(k + \log |\text{starts}|)$, where k is how many new rows must be streamed to cover r (often $k = 0$ for warm caches). Memory is $O(|\text{blocks}|)$, bounded by B_{\max} or by R_{\max} rows of history.

UI integration. On each frame the viewport asks for the *leading* global row (top-left visible), calls `LOCATEROW` to obtain the block and local offset, and renders from there. We prefetch just beyond the viewport by requesting the row at $y_0 + H_{\text{vp}} + \Delta$, which amortizes the streaming cost without over-allocating memory. When the user scrolls back, previously cached blocks are reused; otherwise the binary search still runs in logarithmic time.

Failure modes. Segments with empty selections yield no blocks but are skipped efficiently. If the hierarchy ends before covering the requested row, the driver returns \perp ; the UI interprets this as “no more data.” All pruning policies preserve correctness: they only remove *past* blocks and never create gaps inside the realized suffix.

By applying this method, we render only the cells necessary for the current view, thereby optimizing performance and ensuring smooth user interactions even with large and complex worksheets.

7 Evaluation

The fundamental approach of the Spreadsheet Data Extractor, based on the converter by Aue et al. [3], upon which we build, remains unchanged. The effectiveness of this approach has already been investigated. Aue et al. evaluated the extraction of data from over 500 Excel files. The time required for each file was determined from a sample of 331 processed Excel files comprising 3,093 worksheets. On average, student assistants needed 15 minutes per file and 95 seconds per worksheet.

Our focus is on improving the user experience and optimizing the performance of the prior solution. We enhanced the user experience by displaying the Excel worksheets similarly to how they appear in Excel and by reducing the number of required user interactions through the integration of the selection hierarchy, worksheet view, and output preview into a single interface, thereby reducing context switching. Performance was further improved by implementing incremental loading of Excel files and rendering only the visible cells.

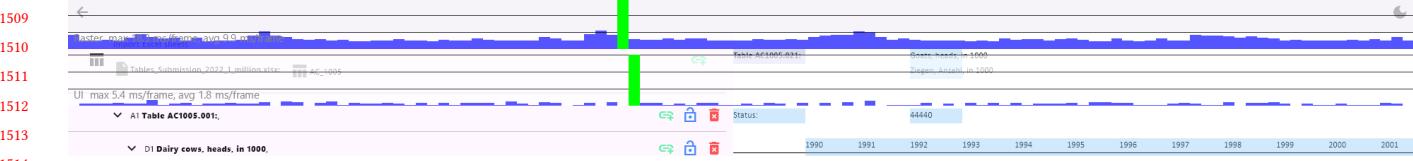


Figure 12: Performance profiling of the SDE. The timeline view shows frame rendering costs (blue) and highlights the maximum (54 ms/frame) and average (18 ms/frame) rendering time.

7.1 Acceleration When Opening Files

We evaluate three systems: our *Spreadsheet Data Extractor* (*SDE*), Microsoft Excel (automated via PowerShell/COM), and the Dart *excel* package. Each condition was repeated ten times and we report distributions as box plots on a \log_{10} time axis. The Dart *excel* package completed only the first run after 343.5680 seconds; runs 2–10 terminated were not possible to finish because it let the test machine run out of memory. Excel: 45.84275 seconds (median); SDE: 0.6565 seconds (median). *SDE* is 45.18625 \times faster than Excel and 342.9115 \times faster than the Dart *excel* package.

Controlling for workload comparability. The multi-worksheet experiment reflects an important user scenario (time-to-first-visual for a selected sheet), but it is not a like-for-like comparison: *SDE* opens only the requested worksheet, whereas the baselines initialise the entire workbook. To control for this confound and establish workload equivalence, we construct a single-worksheet benchmark by pruning the workbook from the example described in 3 Design Philosophy to one sheet and duplicating the table on top of each other until no more fits another table and hence the sheet contains 1,048,548 rows resulting in a file with \sim 35 MB, uncompressed: \sim 282 MB. We then report two cases –*first row* (time-to-first-visual) and *last row* (forces a full parse)—to align its measured cost with eager parsers. Under these identical I/O and parsing conditions, *SDE* achieves 1.229 s vs. 52.756 s for Excel on first rows (42.9 \times), and 5.515 s vs. 52.228 s on the last row (9.47 \times).

Results (overview). Figure 11a demonstrates the practical benefit in a multi-worksheet file: initialising only the selected sheet yields much lower time-to-first-visual. Figure 11b isolates algorithmic differences under identical workload: *SDE* remains \sim 10 \times faster even when a full parse is enforced.

All tests were conducted on a machine with the following specifications: Intel Core i5-10210U quad-core CPU at 1.60 GHz, 16 GB RAM, and a solid-state drive (SSD), running Windows 10 Pro. The version of Microsoft Excel used was Microsoft Office LTSC Professional Plus 2021.

We ran the script 10 times, measuring the time required to open the file and read the values in each iteration. The results of these runtime measurements are presented in Figure 12. The *Spreadsheet Data Extractor* opened the worksheet with a median time of 120 milliseconds and an average time of 178 milliseconds. The first run took 668 milliseconds, possibly because the file was not yet cached and had to be loaded from the disk. In contrast, Excel opened the worksheet with a median time of 40.281 seconds and an average time of 41.138 seconds. The Dart *excel* package [8] used in the previous work took 13 minutes and 15 seconds to open the worksheet

in the first run. The other nine runs could not be completed because an out-of-memory exception was thrown during the second run.

These results demonstrate that the *Spreadsheet Data Extractor* opens worksheets over two orders of magnitude faster than Excel and nearly four orders of magnitude faster than the Dart *excel* package used in prior work.

7.2 Scalability Motivation

While the underlying extraction model remained effective, the previous prototype did not remain interactive on very large sheets. Empirically, on workbooks with hundreds of thousands of rows and, in particular, on sheets near Excel’s 10^6 -row limit, two failure modes dominated:

- (1) **Eager materialization in views.** When the selection view or the output view attempted to realize large regions eagerly, per-frame times rose above 1 s, making panning and selection unusable.
- (2) **Large selection hierarchies.** With many nested selections, highlight updates and duplicate/move previews performed work proportional to the total number of selected cells, causing multi-second pauses per interaction and making operations on large datasets impractical.

These observations motivated the engineering in 6.2 Parsing Worksheet XML with Byte-Level Pattern Matching: (i) byte-level, on-demand parsing of worksheet XML; (ii) viewport-bounded rendering that lays out only $[r_f:r_u] \times [c_f:c_u]$ (Algorithm Scroll extents); (iii) AABB-based filtering of selection sources with cache invalidation (6.4 AABB-Indexed Selection Lookup); and (iv) on-demand flattening of the output table (6.5 Lazy Output Flattening and Row Location). Together these changes bound per-interaction work to the visible area rather than the sheet size.

On a sheet with 10^6 rows and a selection covering all cells, the UI remained smooth during scrolling, sustaining \approx 2 ms per frame, which calculates to \approx 500 FPS. When dragging the scrollbar which causes to fill the whole viewport at once with new content, the frame times rise to about 60 to 80 ms, which calculates to \approx 16 FP which is still acceptable while scrolling through large datasets with 10^6 rows.

8 Conclusion

In this paper, we introduced the *Spreadsheet Data Extractor* [2], an enhanced tool that builds upon the foundational work of Aue et al. [3]. By addressing key limitations of the existing solution, we implemented significant performance optimizations and usability enhancements. Specifically, *SDE* employs incremental loading of worksheets and optimizes rendering by processing only the visible

1625 cells, resulting in performance improvements that enable the tool
 1626 to open large Excel files.

1627 We also integrated the selection hierarchy, worksheet view, and
 1628 output preview into a unified interface, streamlining the data ex-
 1629 traction process. By adopting a user-centric approach that gives
 1630 users full control over data selection and metadata hierarchy defi-
 1631 nition without requiring programming knowledge, we provide a
 1632 robust and accessible solution for data extraction. Our tool offers
 1633 user-friendly features such as the ability to duplicate hierarchies of
 1634 columns and tables and to move them over similar structures for
 1635 reuse, reducing the need for repetitive configurations.

1636 By combining the strengths of the original approach with our
 1637 enhancements in user interface and performance optimizations,
 1638 our tool significantly improves the efficiency and reliability of data
 1639 extraction from diverse and complex spreadsheet formats.

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