

Avoiding the Automation Trap: Designing Human-Centred AI Workflows for Dental Manufacturing

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Avoiding the Automation Trap: Designing Human-Centred AI Workflows for Dental Manufacturing

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Abstract

This industrial case study explores integrating machine learning into high-volume dental manufacturing. Such technologies profoundly influence existing technician workflows and laboratory operations. To address this, a legacy software audit using a localised Cognitive Dimensions of Notation (CDN) framework identified high *Repetitive Viscosity*, *Hidden Task Status*, and *Workflow Rigidity*. This diagnostic phase was driven by structured workshops with the digital technicians. These failings hindered quality control and forced technicians into redundant tasks. To resolve these issues, the project co-designed a human-in-the-loop application that replaced modal menus with a unified 3D editor layout, eliminated hidden states with a visual column-based progress queue, and introduced state serialisation to support flexible task management. Qualitative evaluation confirmed that these design choices effectively resolved the identified cognitive frictions by reducing interaction costs and preventing repetitive editing tasks. While improvements to back-end algorithms halved baseline processing time, successful digital transformation relies equally on workflow redesign and end-user engagement. Ultimately, this method of adapting, localising, and running workshops provides a technique that can be deployed across a wide range of industrial settings when faced with the challenge of the AI-assisted automation trap. This is of particular importance in industrial sectors where machine learning-based solutions risk threatening existing work practices and disrupting established processes.

CCS Concepts

• Human-centered computing → User studies; • Computing methodologies → Artificial intelligence.

Keywords

Human Factors, Cognitive Dimensions of Notation, Artificial Intelligence, Machine Learning

ACM Reference Format:

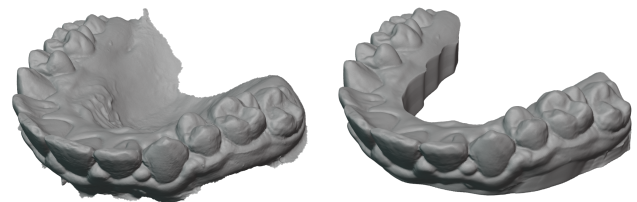
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1 Introduction

This paper presents a Knowledge Transfer Partnership (KTP) academia-industry collaboration modernising dental manufacturing at S4S Dental Laboratory. The operational domain centres on the digital preparation of raw intraoral scans into 3D-printable models (see Figure 1), including automated cleaning, model basing to standard thickness, levelling, and patient-specific labelling. Driven by the business threat of relying on closed-loop, proprietary software, this project used structured workshops to co-design a human-centred alternative. To measure the operational bottleneck, a black-box audit of the legacy software revealed a 59% failure rate from poor automated levelling and excessive model thickness. These algorithmic failures force technicians into repetitive manual computer-aided design (CAD) edits, slowing production. A subsequent formative assessment identified key usability problems, specifically high interaction costs and hidden system states.



(a) Raw Scan

(b) Processed Scan

Figure 1: Before and after the dental model preparation workflow. (A) The raw, unlevelled intraoral scan presenting a high cognitive load for manual editing. (B) The final, print-ready manifold mesh.

To address these failures, a bespoke, in-house artificial intelligence (AI) solution is introduced. Introducing machine learning in industrial settings often triggers AI anxiety and concerns of employment risk [7, 10]. Intrinsic to the KTP philosophy is embedding knowledge within the organisation. By requiring a deep understanding of business operations and values, this approach de-risks actual technology adoption, which is a growing necessity with AI solutions becoming more common. Consequently, automation must be framed collaboratively, accounting for how automation interacts with human workflows, interruptions, and decision-making [6].

This work details user requirement gathering, interface co-design, and machine learning implementation. Beyond reporting a successful industrial deployment, this paper offers three practical lessons for HCI practitioners: adapting CDN to industrial workflows, using participatory design to mitigate resistance to automation adoption, and illustrating that workflow redesign can yield greater operational impact than algorithmic optimisation alone.

2 Methodology

To ensure the application resolved operational barriers, a user assessment engaged all eight digital technicians (two digital production leaders and six operators) at S4S Dental Laboratory. Capturing both high-level oversight and daily production friction, the research adapted a questionnaire developed from the CDN framework [9]. This framework was selected as a lightweight, low-resource method for formulating alternative designs [8]. A small team of operators and the researcher reviewed and adapted the eighteen questions of the CDN-based assessment, ensuring domain localisation for efficient and effective user engagement. This localisation activity resulted in framing the questions around three core workflow concepts: File Input, 3D Editing, and Exporting.

To avoid operational downtime, the questionnaire was completed individually over one week. Individuals were encouraged to discuss amongst themselves and also engage the researcher. The researcher then facilitated two one-hour workshops to discuss responses, encourage reflection, and document findings.

2.1 Assessment Findings

Supported by high quantitative difficulty ratings across core tasks, the CDN-based assessment revealed that the legacy software heavily penalised operators for minor errors. For instance, correcting a typographical error on a patient label forces the user to restart the entire queue, a problem characterised as *Repetitive Viscosity* [2]. This high time cost actively discourages users from fixing minor quality issues, which bypasses quality control, drives up error rates, and reduces overall operator throughput. Furthermore, a lack of visual indicators made tracking edited scans difficult, creating a *Hidden Status* problem that, coupled with poor error management, directly impacted quality. The user interface relies on high-speed keyboard shortcuts for accepting files, which inadvertently encourages a reflexive behaviour where users simply "spam the spacebar" to clear their queues. This rapid interaction design overrides any opportunity for reflective quality control and increases the likelihood of downstream manufacturing errors. Finally, the study identified a critical lack of flexibility, as the system enforces a strict linear progression without state serialisation, meaning application states cannot be saved to return to later. Consequently, technicians cannot pause incomplete tasks for urgent rush jobs without losing progress, demonstrating a lack of *Provisionality* and a high degree of *Workflow Rigidity* that fundamentally misaligns with the interruption-prone nature of a commercial dental laboratory.

3 Designing the Solution

The technical solution was conceptualised directly alongside the S4S team. Rather than the computationally heavy, intricate tooth segmentation common in literature [3, 5, 12], the project focused

on a pragmatic "dental arch" segmentation task. To support this, technicians manually annotated a bespoke dataset of 348 intraoral scans. They utilised domain expertise to explicitly define boundaries between the foreground dental arch and background data (e.g., palatal vault, vestibules, and scan artefacts). This participatory approach embedded human domain knowledge within the machine learning pipeline to ensure the resulting automation met strict commercial requirements.

The usability bottlenecks identified during the prior CDN-based assessment directly informed the new interface design. To resolve the *Hidden Status* problem, the queue was redesigned into a visual, column-based layout, allowing operators to track the exact progress of each scan. Furthermore, to reduce interaction costs and streamline the daily workflow, the cumbersome modal separation between the file list and the 3D editor was removed. Routing users directly into the 3D editor upon selecting a file significantly reduced the cognitive load required to navigate between tasks.

Notably, the interface was designed around a human-in-the-loop paradigm [11]. While the machine learning backend automates the heavy lifting of arch segmentation, the digital technician remains the authority on the quality of the output. The unified 3D viewer ensures that operators can efficiently perform mandatory quality control checks and execute targeted manual edits before finalising the model. Additionally, implementing state serialisation directly resolved the severe *Repetitive Viscosity*; by allowing operators to pause tasks, handle urgent interruptions, and resume edits without losing data, the application successfully accommodates the highly unpredictable workflow of a commercial dental laboratory.

To eliminate disjointed workflows, this unified web application integrates a hardware-accelerated backend. To process high-resolution mesh data within strict hardware constraints and avoid latency-based friction, the system applies automated post-processing routines to reliably output manifold, "print-ready" meshes. By balancing rapid AI automation with essential domain expert validation, this architecture effectively handles high-volume throughput demands.

4 Evaluation

An initial qualitative expert evaluation with the S4S Digital team assessed whether the UX interventions resolved the identified cognitive frictions. Regarding *Hidden Status*, leadership noted that having "each point of progress of each scan separated into columns makes searching for a specific file easier" and "gives a better idea of progress through the actual process". Eliminating modal popups improved focus and task flow, with users reporting a reduction in unnecessary interaction steps, stating that "being directed straight to the 3D editor is the natural next step" that "reduces frustration and generally speeds up the process". State serialisation solved the lack of *Provisionality*. Leaders stated "giving the user the ability to go back a step, but still save current progress avoids having to edit the same scan the same way multiple times", ensuring "less repeated tasks when using the software". Coupled with a 50% reduction in baseline processing time, the prototype successfully integrates algorithmic efficiency with human-centred design to reduce redundant tasks.

5 Discussion and Conclusion

Beyond reporting a successful commercial deployment, this study uncovers broader structural insights regarding human-AI collaboration. Analysing these workflow dynamics reveals critical implications for future research and practice across three primary areas.

Firstly, for *Human-Centred AI*, integrating AI into manufacturing requires more than algorithmic accuracy [4]. This project highlights the automation paradox [1]; deploying fast machine learning models within rigid workflows creates human bottlenecks that nullify computational speed gains, implying that structural usability design is as essential as algorithmic optimisation.

Secondly, for *Industry*, machine learning risks threatening established work practices and alienating the workforce. To de-risk technological transitions, automation must be framed as a collaborative tool rather than an autonomous replacement. Commercial dental laboratories operate under high-volume throughput demands where operators must frequently context-switch between automated processing and precise manual CAD edits. When interfaces do not account for these operational interruptions, the system inadvertently creates bottlenecks where progress is stalled or data is lost. Consequently, dental labs should prioritise evaluating workflow fluidity and interface design before investing in higher-performance models, as the true operational value lies in supporting the technician's ability to manage production flow effectively.

Finally, for *Usability Research*, this study demonstrates that the CDN-based framework is a lightweight tool that can be successfully adapted to contemporary AI contexts. Using just a small number of participatory workshops addresses immediate usability issues while embedding technical knowledge and fostering long-term user ownership within the organisation. Future work will maintain end-user engagement through iterative assessments to ensure user acceptance during the complete solution rollout.

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