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RESEARCH AND EDUCATION

Comparative cost-analysis for removable complete dentures fabricated with conventional, partial, and complete digital workflows

Lucio Lo Russo, DDS, PhD,[a] Khrystyna Zhurakivska, DDS, PhD,[b] Laura Guida, DDS,[c] Konstantinos Chochlidakis, DDS, MS,[d] Giuseppe Troiano, DDS, PhD,[e] and Carlo Ercoli, DDS, MBA[f]

ABSTRACT

Statement of problem. Comparative cost-analysis related to different manufacturing workflows for removable complete denture fabrication is seldom performed before the adoption of a new technology.

Purpose. The purpose of this study was to compare the clinical and laboratory costs of removable complete dentures fabricated with a conventional (workflow C), a partial digital (workflow M), and a complete digital (workflow D) workflow and to calculate the break-even points for the implementation of digital technologies in complete denture fabrication.

Material and methods. Clinical and laboratory costs for each of the investigated workflows and the manufacturing options related to denture base and denture teeth fabrication were collected from 10 private Italian dental laboratories and clinics. The selected variables included the clinical and laboratory manufacturing time needed to complete each workflow (opportunity cost); costs for materials, labor, packaging, and shipping; and capital and fixed costs for software and hardware, including maintenance fees. The effect of manufacturing workflows and their options on the outcomes of interest was investigated by using generalized estimated equations models (α=.05). Cost minimization and sensitivity analysis were also performed, and break-even points were calculated for the equipment capital costs related to the implementation of workflows M and D.

Results. From a laboratory standpoint, workflows M and D and related manufacturing options significantly (P<.001) reduced manufacturing time (5.90 to 6.95 hours and 6.30 to 7.35 hours, respectively), and therefore the opportunity cost of each denture compared with workflow C. Workflow M allowed variable costs savings between 81 and 169 USD, while workflow D allowed for an additional saving of 34 USD. The sensitivity analysis showed that the break-even point related to the capital investment for the equipment needed to implement workflows M and D could be reached, depending on the manufacturing options adopted, between 170 and 933 dentures for workflow M and between 73 and 534 dentures for workflow D. From a clinical standpoint, workflows C and M were almost identical. Conversely, workflow D, which included intraoral scanning, required 1 fewer appointment, saving 0.6 hours of chairside time and about 14 USD for materials compared with M.

Conclusions. Digital workflows (partial and complete digital workflows) were more efficient and cost-effective than the conventional method of fabricating removable complete dentures, with workflow D showing the lowest opportunity and variable costs and break-even point. Savings increased when stock denture teeth were replaced with milled denture teeth and still further with the adoption of 3-dimensionally (3D) printed denture teeth. Milling equipment and materials for denture base fabrication were more expensive than those for 3D-printing. Milling monobloc dentures reduced opportunity and labor costs but increased material cost. (J Prosthet Dent 2024;131:689-96)

[a]Professor of Oral Diseases, Department of Clinical and Experimental Medicine, School of Dentistry, University of Foggia, Foggia, Italy.
[b]Researcher, Department of Clinical and Experimental Medicine, School of Dentistry, University of Foggia, Foggia, Italy.
[c]Private practice, Vallesaccarda, Avellino, Italy.
[d]Associate Professor and Program Director, Department of Prosthodontics, Eastman Institute for Oral Health, University of Rochester, Rochester, NY.
[e]Aggregate Professor of Oral Diseases, Department of Clinical and Experimental Medicine, School of Dentistry, University of Foggia, Foggia, Italy.
[f]Professor, Prosthodontics and Periodontics, and Chair, Department of Prosthodontics, Eastman Institute for Oral Health, University of Rochester, Rochester, NY.

Clinical Implications

The application of digital workflows, especially those related to additive technologies in the manufacturing of removable complete dentures, may represent an affordable, cost-effective, and profitable opportunity to satisfy the oral rehabilitation needs of edentulous patients.

An individual with complete edentulism meets the criteria for being both physically[1] and psychologically[2] impaired and disabled. Oral rehabilitation after tooth loss has been shown to significantly improve oral health-related quality of life.[3] Removable dentures still remain an option for the oral rehabilitation of patients with edentulism, and improving access to complete denture treatment would be a significant benefit.[4]

While removable dentures can be fabricated with labor-intensive analog technologies, the adoption of computer-aided design and computer-aided manufacturing (CAD-CAM) has simplified their fabrication and is preferred to conventional workflows.[5] Oral health-related quality of life measures in patients receiving digitally manufactured removable prostheses have been reported to be similar to those of individuals receiving conventionally fabricated dentures.[6] Nonetheless, specific procedures in the digital workflows are preferred by the patient; for example, patient satisfaction with intraoral scans is greater than that with conventional impression procedures.[7] Additionally, there is evidence that the adoption of a digital removable denture workflow improves several aspects related to complete denture outcomes, including patient- and dentist-assessed clinical outcomes,[5] practice ergonomics and treatment efficiency (fewer patient visits required to unit of production),[6] laboratory efficiency,[6] manufacturing standardization,[8] denture retention[9] and fit,[10,11] denture tooth stability during processing or manufacturing,[12] visualization of function[13] and esthetics,[14] and material properties and biocompatibility.[15]

The reported advantages of digital workflows would suggest they be adopted in clinical and laboratory practice. Nonetheless, incorporating digital technologies and materials into removable complete denture prosthodontics may be challenging because of real or perceived barriers such as psychological (willingness to acquire new knowledge and expertise), practical (training time and learning curve required to gain sufficient expertise, equipment and space, availability of labor), and financial (capital and operational investment) issues. These barriers may impede, delay, or complicate the implementation of digital workflows in dental practices and laboratories. Indeed, concerns related to capital and operational costs related to digital technologies have been reported as the main barriers to the adoption of digital technologies in dental schools.[16]

Revenue-cost analysis related to capital and operational aspects for implementing digital workflows has seldom been investigated, especially in removable prosthodontics. In a university setting, a cost-benefit analysis for replacing an analog clinical curriculum with a 4-appointment digital one for the fabrication of complete dentures has been shown to decrease material and chair time costs.[17] Similarly, a 2-visit digital denture protocol as compared with a conventional denture protocol showed lower overall costs, including chairside and laboratory time, even though the material costs were greater.[18]

This lack of information is even greater when related to private practice, which is, generally, the main setting for the delivery of dental care. Assuming that conventional denture manufacturing techniques are already widely available in dental laboratories and used as a reference and that patient costs are not significantly affected, data regarding revenue-cost analysis could be broadly assumed to be a function of cost-minimization strategies (actual costs compared with those related to alternative interventions). These considerations may differ for the clinical and/or laboratory aspects of current digital workflows. For example, most of the systems reported in the literature have been based on conventional intraoral impressions,[19,20] which are then digitized. This limits the incorporation of direct digital solutions (data acquisition and elaboration) in the clinical setting and is different from a complete clinical and laboratory workflow where intraoral scans of the edentulous arches and extraoral face scanning are used and combined to further optimize clinical and laboratory fabrication processes.[21] The rationale behind the use of intraoral scans for removable dentures and their distinctive features has been reported previously.[21,22]

With the overall aim of investigating the cost-effectiveness and profitability of implementing digital technologies for removable complete dentures, the objective of the present practice-based study was to perform a cost-minimization analysis for the adoption of previously reported digital denture workflows,[20,21] with the conventional manufacturing technique as a reference. The null hypothesis was that no difference would be found in costs between the conventional denture fabrication technique and selected digital denture workflows.

MATERIAL AND METHODS

The study was designed according to the Consolidated Health Economic Evaluation Reporting Standards (CHEERS).[23] The analysis was carried out from the perspective of an existing clinical or laboratory dental

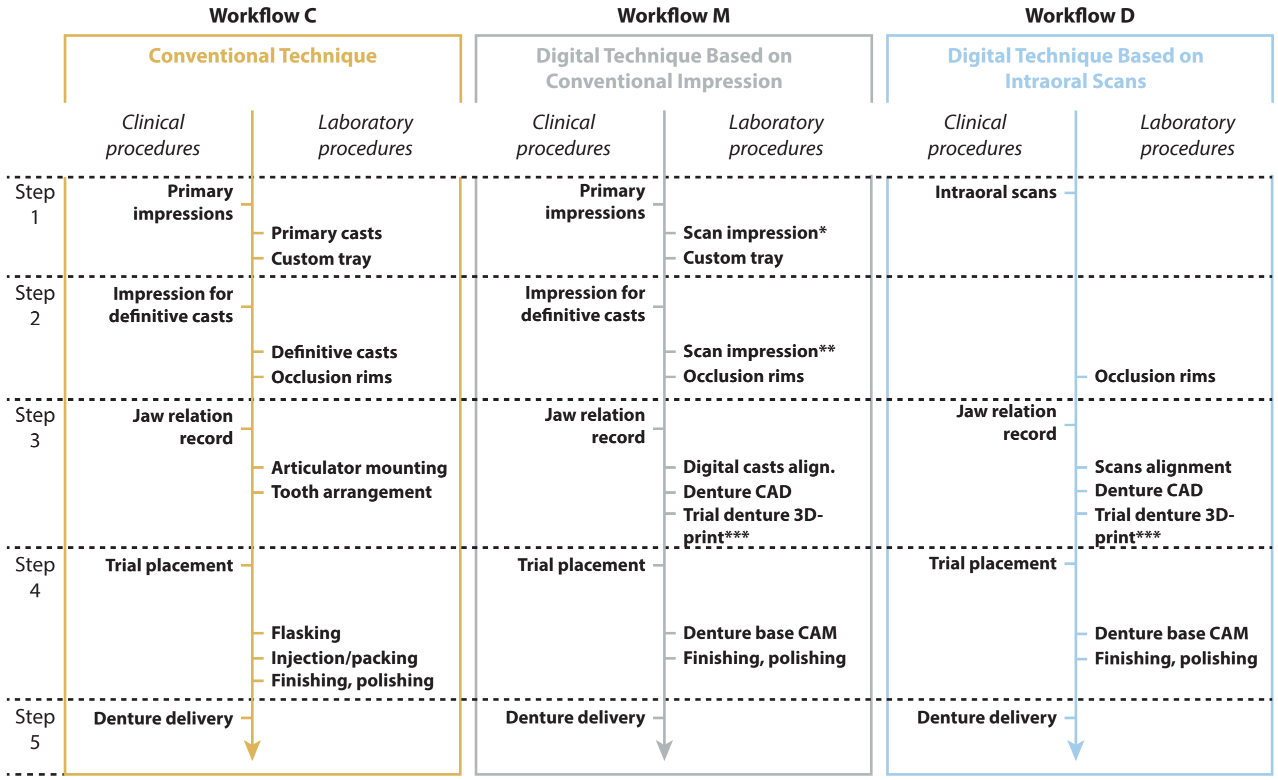

Figure 1. Outline of investigated workflows. *Option of creating stone casts from impressions and then scanning not considered; **output of this task: digital casts; ***option of milling evaluation prostheses not considered. CAM, computer-aided manufacturing.

practice and intended to transition from conventional techniques to digital workflows for the design and fabrication of removable complete dentures. Three workflows were examined: the conventional analog workflow (workflow C), a mixed analog-digital workflow where a conventional intraoral impression is obtained and then digitized in the laboratory[20] (workflow M), and a fully digital workflow further incorporating an intraoral scan[21] (workflow D). Clinical and laboratory procedures for each of the investigated workflows are outlined in Figure 1. In addition, several options for denture fabrication were compared according to the technology used for the denture base and tooth manufacturing in workflow M or D (Table 1).

For each workflow, marginal costs (cost related to the production of a single-arch additional complete denture) were recorded. The costs were estimated based on data collected from 10 small private Italian dental laboratories and practices (number of employees: 2 to 6). Practice personnel were asked to fill out a standardized data-collection form with information related to the time needed to accomplish each manufacturing step (opportunity cost), costs for materials (including consumables), labor (determined as hourly cost multiplied by time spent for each procedure), packaging and shipping, and capital investment and operational costs for software programs and hardware technologies related to digital workflows, including support and maintenance fees. Costs were collected in Euros (EUR), as in 2021, and converted to United States dollars (USD) by using a conversion rate of 1.15.

Table 1. Options considered for comparison according to denture base and tooth fabrication technology

Denture Fabrication	Workflow C		Workflow M or D	
	Denture Base	Teeth	Denture Base	Teeth
Option 1	Injection/packing	Stock teeth	Milled	Stock teeth
Option 2	Injection/packing	Stock teeth	Milled	Milled
Option 3	Injection/packing	Stock teeth	Milled	3D printed
Option 4	Injection/packing	Stock teeth	3D printed	Stock teeth
Option 5	Injection/packing	Stock teeth	3D printed	Milled
Option 6	Injection/packing	Stock teeth	3D printed	3D printed
Option 7	Injection/packing	Stock teeth	Milled in monobloc	

Data were extracted, and the corresponding descriptive statistics obtained; the effect of workflows and their options (Table 1) on the outcomes of interest was investigated among and within practices by using generalized estimated equation (GEE) models. The GEE methodology was used to model and control the within-unit data. All outcomes of interest were individually investigated as dependent variables in the GEE models. For each of them, the practice was used as a subject variable. Workflows and their options were

Table 2. Marginal costs and time spent for laboratory procedures detailed in Figure 1: data (mean ±standard deviation) from performed survey

Option	Workflow	Manufacturing Time (Opportunity Cost) (h)	Costs					
			Materials and Consumables (USD)	Packaging and Shipping (USD)	Labor (USD)	Software[b] (USD)	Hardware[b] (USD)	Annual fees[b] (USD)
Option 1	C[a]	8.5 ±0.7	98.09 ±7.7	55.2 ±4.4	117.3 ±9.2	0	0	0
–	M	2 ±0.16	113.96 ±8.9	48.3 ±3.8	27.6 ±2.2	13 800 ±1092.5	61 525 ±4864.5	2300 ±184
–	D	1.6 ±0.13	112.7 ±8.9	20.7 ±1.8	22.08 ±1.7	13 800 ±1092.5	47 725 ±3772	2300 ±184
Option 2	M	1.8 ±0.14	78.31 ±6.2	48.3 ±3.8	21.6 ±1.7	13 800 ±1092.5	61 525 ±4864.5	2300 ±184
–	D	1.4 ±0.11	77.05 ±5.9	20.7 ±1.8	19.32 ±1.5	13 800 ±1092.5	47 725 ±3772	2300 ±184
Option 3	M	2.2 ±0.17	55.3 ±4.4	48.3 ±3.8	30.36 ±2.3	13 800 ±1092.5	67 275 ±5318.7	2300 ±184
–	D	1.8 ±0.14	54.05 ±3.4	20.7 ±1.8	24.84 ±1.9	13 800 ±1092.5	53 475 ±4220.5	2300 ±184
Option 4	M	2.1 ±0.16	74.86 ±5.8	48.3 ±3.8	28.98 ±2.3	4025 ±437	24 725 ±1955	1150 ±97.7
–	D	1.7 ±0.13	73.6 ±5.7	20.7 ±1.8	23.46 ±1.8	4025 ±437	10 925 ±862.5	1150 ±97.7
Option 5	M	2.2 ±0.18	40.36 ±3.2	48.3 ±3.8	30.36 ±2.3	13 800 ±1092.5	67 275 ±5318.7	2300 ±184
–	D	1.8 ±0.14	39.1 ±3.1	20.7 ±1.8	24.84 ±1.61	13 800 ±1092.5	5347 ±4220.5	2300 ±184
Option 6	M	2.6 ±0.2	17.36 ±1.4	48.3 ±3.8	35.88 ±2.9	4025 ±437	24 725 ±1955	1150 ±97.7
–	D	2.2 ±0.17	16.1 ±1.1	20.7 ±1.8	30.36 ±2.3	4025 ±437	10 925 ±862.5	1150 ±97.7
Option 7	M	1.55 ± 0.1	117.99 ±9.3	48.3 ±3.8	21.39 ±1.72	13 800 ±1092.5	61 525 ±4864.5	2300 ±184
–	D	1.15 ±0.1	116.72 ±8.6	20.7 ±1.8	15.87 ±1.15	13 800 ±1092.5	47 725 ±3772	2300 ±184

C, conventional workflow; D, digital workflow; M, partial digital workflow; USD, United States dollar. [a]Workflow C identical for all options. [b]Only for workflow M and D.

used as within-subject variables, and an unstructured correlation matrix was considered. Workflows and their options were also used as factors. All statistical analyses were performed by using a statistical software program (IBM SPSS Statistics, v25.0; IBM Corp) (α=.05).

The TreeAge Pro Healthcare 2021 (TreeAge Software, LLC) software program was used to perform the cost-minimization analysis for the compared workflows, based on the assumption that the definitive prostheses would have comparable effectiveness and quality.[6] It was also assumed that no additional revenue would be obtained by the dentist (from the patient) or by the dental laboratory technician (from the dentist) when adopting workflow M or D. Thereafter, a sensitivity analysis was performed, and break-even points (number of dentures where total revenue equals total cost) for equipment capital investment and operational costs related to the adoption of workflows M and D were calculated.

RESULTS

The mean values for marginal production times (opportunity costs) and costs are reported in Table 2, and the corresponding differences across workflows in Table 3. From a laboratory standpoint, workflows M and D and related manufacturing options significantly (P<.001) reduced manufacturing time (5.90 to 6.95 hours and 6.30 to 7.35 hours, respectively), and therefore opportunity cost for each denture compared with workflow C. Workflow M allowed variable cost savings between 81 and 169 USD, while workflow D allowed for an additional saving of 34 USD. Variability existed among different options of digital workflows; GEE analyses showed that workflows and their options had a significant effect for all outcomes of interest (P<.001). Rankings for efficiency and cost-effectiveness (or profitability), as derived from the decision-analytic tree for the cost-minimization analysis, are reported in Table 4. The pattern of variability across workflow options was the same for both M and D; hence, Table 4 rankings are applicable to both workflows.

The average long-term capital investment required for a laboratory to transition from workflow C to workflow M varied between 28 750 and 81 075 USD according to the different options considered. Such an investment was decreased, on average, by 13 800 USD when considering workflow D because this particular workflow, based on intraoral digital scans, did not require hardware equipment to scan analog impressions. Adopting workflow M or D also required fixed yearly costs between 1150 and 2300 USD for equipment operation, support, and maintenance, which did not differ between workflows M and D. The sensitivity analysis (expected value generated by cost minimization) and the corresponding break-even points are reported in Table 5 and illustrated in Figure 2. The analysis was easily generalizable, based on the workload, which could be applied to dental laboratories of similar scale. It showed that 170 to 933 additional dentures were necessary to reach the break-even point for the various options related to workflow M, while only 73 to 534 dentures were similarly needed for workflow D.

From a clinical point of view, conventional dentures (workflow C) and digital dentures made from digitized conventional intraoral impressions (workflow M) are almost identical. Conversely, workflow D saved at least 1

Table 3. Differences across workflows for time and costs

		Option1 Milled base Stock teeth	Option 2 Milled base Milled teeth	Option 3 Milled base 3D printed teeth	Option 4 3D printed base stock teeth	Option 5 3D printed base milled teeth	Option 6 3D printed base 3D printed teeth	Option 7 Milled in monobloc
Workflow M - Workflow C								
Time spent for procedures (h)		-6.5	-6.7	-6.3	-6.4	-6.3	-5.9	-6.95
Variable costs (USD)	Materials and consumables	15.9	-19.8	-42.8	-23.2	-57.7	-80.7	19.9
—	Packaging and shipping	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9
—	Labor	-89.7	-92.46	-86.94	-88.3	-86.9	-81.4	-95.9
—	Total difference for variable costs	-80.7	-119.14	-136.6	-118.45	-151.6	-169	-82.9
Long-term investment (USD)	Software	13 800	13 800	13 800	4025	13 800	4025	13 800
—	Hardware	61 525	61 525	67 275	24 725	67 275	24 725	61 525
—	Total long-term investment	75 325	75 325	81 075	28 750	81 075	28 750	75 325
Fixed yearly costs (USD)	Annual fees	2300	2300	2300	1150	2300	1150	2300
Workflow D - Workflow M								
Time spent for procedures (h)		-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
Variable costs (USD)	Materials and consumables	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3
—	Packaging and shipping	-27.6	-27.6	-27.6	-27.6	-27.6	-27.6	-27.6
—	Labor	-5.5	-5.5	-5.5	-5.5	-5.5	-5.5	-5.5
—	Total difference for variable costs	-34.4	-34.4	-34.4	-34.4	-34.4	-34.4	-34.4
Long-term investment (USD)	Software	0	0	0	0	0	0	0
—	Hardware	-13 800	-13 800	-13 800	-13 800	-13 800	-13 800	-13 800
—	Total difference for long-term investment	-13 800	-13 800	-13 800	-13 800	-13 800	-13 800	-13 800
Fixed yearly costs (USD)	Annual fees	0	0	0	0	0	0	0

appointment, 0.6 hours of chair-side time, and about 14 USD for materials. Sensitivity analysis for clinical procedures between workflows M (same as C) and D was not carried out, as it required data outside the scope of the present study.

DISCUSSION

The null hypothesis that no difference in costs would be found between the conventional denture fabrication technique and selected digital denture workflows was rejected, as the costs across the investigated workflows were different. In a simplistic way, a denture is composed of a base upon which denture teeth are attached. For the conventional technique, stock teeth, after selection and adaptation, are incorporated into the base with the established methodology. Conversely, for digital dentures, both the fabrication of the denture base and the teeth can follow different paths. The denture base and teeth can be fabricated either by additive (3D-printing) or subtractive (milling) technologies[11] which, of course, require different equipment, materials, and processing. These need to be acknowledged to properly address their corresponding costs. For this reason, several selected options for the digital workflows have been considered in the present study and incorporated into the cost-minimization and sensitivity analyses; other factors or

Table 4. Rankings for efficiency and profitability of options for digital workflows (M or D)

Ranking	Reduction of Working Time	Reduction of Material Costs	Reduction of Staff Costs	Reduction of Total Variable Costs	Reduction of Total Long-Term Investment
1	Option 7	Option 6	Option 7	Option 6	Option 4 Option 6
2	Option 2	Option 5	Option 2	Option 5	Option 1 Option 2 Option 7
3	Option 1	Option 3	Option 1	Option 3	Option 3 Option 5
4	Option 4	Option 4	Option 4	Option 2	—
5	Option 3	Option 2	Option 3	Option 4	—
6	Option 5	Option 1	Option 5	Option 7	—
7	Option 6	Option 7	Option 6	Option 1	—

Rank 1: greatest reduction.

Table 5. Break-even points: number of dentures needed to be manufactured to cover long-term investment by means of variable cost minimization

		Number of Single-Arch Dentures Needed to Be Fabricated to Cover Investment		Number of Single-Arch Dentures Needed to Be Fabricated to Cover Annual Fees	
Models Option	**Option Details**	**Workflow M**	**Workflow D**	**Workflow M**	**Workflow D**
Option 6	3D printed base 3D printed teeth	170	73	7	6
Option 4	3D printed base Carded teeth	243	98	10	8
Option 5	3D printed base Milled teeth	535	362	15	12
Option 3	Milled base 3D printed teeth	593	393	17	13
Option 2	Milled base Milled teeth	632	401	19	15
Option 7	Milled in monobloc	908	525	28	20
Option1	Milled base Carded teeth	933	534	28	20

Workflow options reported in ascending order.

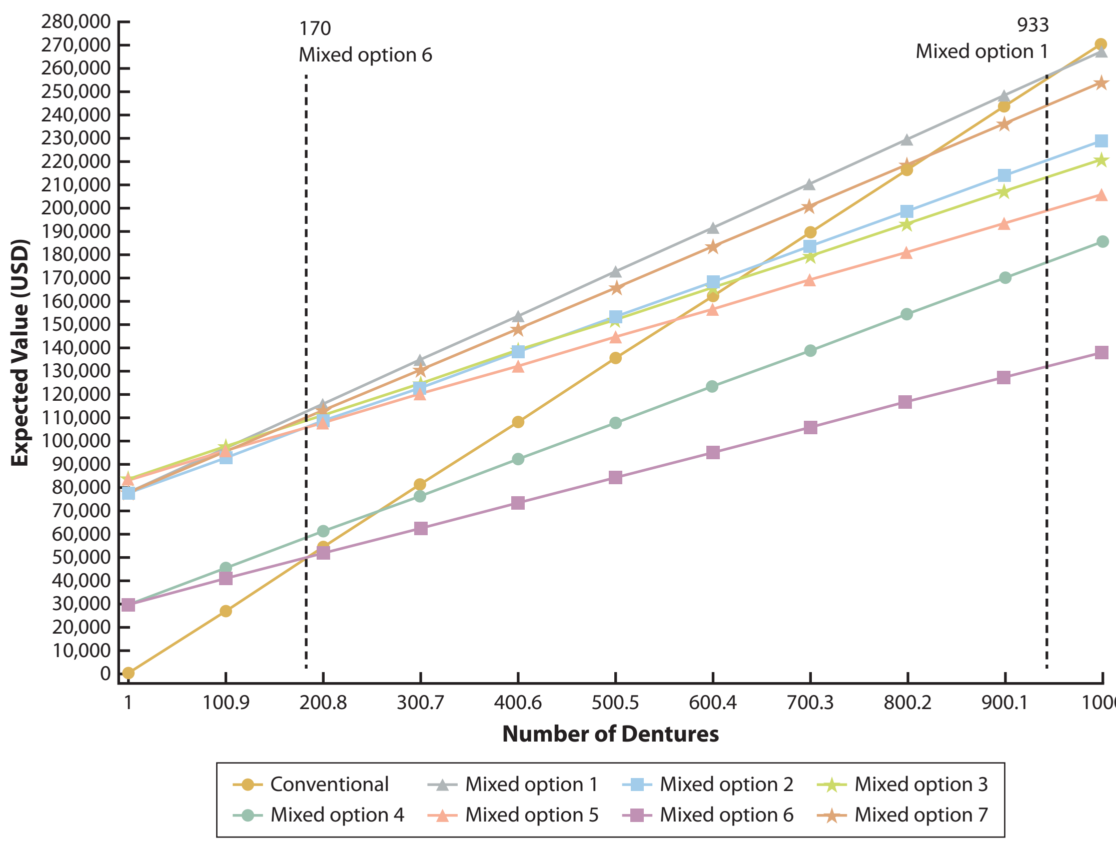

Figure 2. Sensitivity analysis of workflow M versus workflow C: expected values in United States dollars (USD) generated by cost minimization as function of number of manufactured dentures.

combinations thereof related to the technical or clinical aspects of removable complete denture fabrication were beyond the scope of the present study.

Considering variable costs, when stock teeth are used, the conventional technique (workflow C) is characterized by reduced costs for materials (on average 16 USD per denture) in comparison with digital workflows (M and D). However, the significantly more labor-intensive nature which characterizes workflow C (5.90 to 7.35 hours greater than M or D for additional denture) largely increases the opportunity costs required to complete the manufacturing process and makes such a workflow the least cost-effective or profitable, which is consistent with published data.[18] Digital manufacturing workflows (M and D) are characterized by improved efficiency and, especially for workflow D, more straightforward logistics (transferring files is faster and less expensive than shipping physical objects) both from the clinical and laboratory point of view. In addition, electronic transmission of acquired data between the clinic and the laboratory is beneficial for infection control and breaks the chain of potential transmissible infections that could also affect costs.

Because of the improved efficiency which characterizes workflow M and D, considerable cost savings, ranging from 81 to 169 USD, can be realized for each manufactured denture. The extent of such a saving interval confirms the different efficiency and profitability of additive and subtractive technologies and the materials used for removable denture fabrication. In fact, costs decrease while transitioning from using stock denture teeth to milled denture teeth and even more to 3D-printed denture teeth. In addition, using subtractive technology and materials to fabricate denture bases is currently more expensive than using 3D-printing. Nonetheless, the reduced working time, with associated reduced personnel costs, makes subtractive technology a preferable option (Table 4).

The present results indicated that 3D-printing is the most cost-effective and profitable option for complete denture fabrication. With regard to its efficiency, the data reported in Tables 2 and 3 seem to indicate that 3D-printing requires longer manufacturing times because of postprocessing. Nonetheless, the reported data refer to the manufacturing of a single denture, making the indicated difference true only when additive and subtractive technologies are compared for the fabrication of a single denture at a time. While this is true for current subtractive technologies, the efficiency of additive technologies can be enhanced by printing several dentures at the same time. Although many other factors might influence the adoption of additive technologies, such as long-term denture service, material biocompatibility, dimensional stability,[24] residual monomer levels, stability of mechanical properties and color over time, compatibility with conventional relining materials, and patient-centered outcomes,[11] the 3D-printing of complete dentures constitutes an affordable option for the millions of people, even in developed countries,[4] who are in need of affordable removable prostheses.

Sensitivity analysis indicated that the break-even point for the adoption of digital workflows varies depending on the option adopted for denture base and teeth fabrication. However, a capital investment could be completely covered, keeping revenue unchanged and not considering depreciation-related tax advantages, by the expected net income generated by cost reduction for a moderate number of complete dentures (Table 5).

Limitations of the present study included that the costs were surveyed from small dental practices and laboratories; thus, the current analysis may not completely fit larger dental laboratories. However, for larger dental laboratories, economies of scale and possibly scope may increase savings related to digital workflows and, hence, affect the application and effectiveness of the current findings. The investigated digital workflows were based on open technologies,[20,21] which may minimize costs but make the present results less relevant for closed systems. The specific features of those systems (for example, system-specific trays or instruments, exclusive dental materials, or system-inherent techniques) may affect cost minimization and would be addressed by specific analysis of the particular system. The present results are applicable to the fabrication of a new denture. Techniques to digitally duplicate existing dentures have become popular but were not considered. In addition, the costs of learning new technologies and procedures related to digital workflows were not considered in the present study because their standardization (number of participants, training modalities, length of the learning curve, coexistence of conventional and digital workflows) is quite complex to model and the corresponding results might not be meaningful.

Furthermore, sensitivity analysis and the break-even point related to the clinical adoption of workflow M or D were not carried out. This analysis, which requires a precise estimation of private practice characteristics such as infrastructure and operational costs and the depreciation and amortization of tangible and intangible assets, was outside the scope of the present study. In addition, the capital expenses for the adoption of digital workflows as described would be expected to benefit other services offered by a dental clinic, such as the fabrication of fixed and implant prostheses. As this would compromise the reliability and significance of the sensitivity analysis, it was not conducted because of differences in the clinical procedures.

CONCLUSIONS

Based on the findings of this cost analysis study, the following conclusions were drawn:

1. Considering variable costs, including opportunity cost, digital workflows are characterized by significantly lower cost than the conventional technique for complete denture fabrication.
2. The greatest efficiency and cost minimization (for both variables, costs and long-term investment) can be obtained with 3D-printing.
3. Transitioning from the use of stock teeth to milled or 3D printed teeth provides additional reduction in cost.

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Corresponding author:
Prof Lucio Lo Russo
Via Serro D'Annunzio, 20
83050 Vallesaccarda, Avellino
ITALY
Email: lucio.lorusso@unifg.it

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