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A Comparative Study Of Hotpress, CAD/CAM Casting And Shell Sintering Technology (SST) For Porcelain Dental Crown Production

Lílian Cristina Côcco[1], Marlon Wesley Machado Cunico[2]*

1.Zirclab Medical Devices, Unit 211, The Lightbulb, 1 Filament Walk, Wandsworth, SW18 4GQ, London, United Kingdom.

2.Concept 3D, Pedro Ivo Street, 298, r 23, 80010-020, Curitiba, Paraná, Brazil.

ABSTRACT

This study was conducted to determine the economic impact of producing dental prostheses using three alternative methods: traditional casting (hotpress), CAD/CAM casting, and shell sintering technology (SST). In order to evaluate costs, get accurate information, and quantify overhead aspects, deterministic bottom-up economic models were used. The inputs utilised to create the models focused on the costs of materials, equipment, labour, and the time required to complete each stage of the porcelain crown manufacturing process. The economic models revealed that the SST method has the lowest material and labour costs, while the hotpress technique has the lowest equipment expenses. However, hotpress had the highest manufacturing costs and is thus the most expensive technology, with an average return on investment of 17% and a payback period of 5.9 years. In second place, despite the significant material and equipment acquisition costs, the CAD/CAM Casting process achieved a 35% ROI with an average payback period of 2.9 years. Even though these economic values are adequate, the SST technology revealed extremely advantageous values for low and large-scale processing of dental crowns, achieving above 180% ROI with a payback of 0.5 years. The key finding from all the data is that SST has excellent economics and has the potential to improve the dental prosthesis manufacturing industry.

Keywords: Dental crown; Hotpress; CAD/CAM; Dental prostheses; Cost Model; SST

*Corresponding Author Email: marloncunico@yahoo.com.br
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INTRODUCTION

Effective and flexible production processes are the foundation of everyday business success in today's modern manufacturing environment. Buyers demand creative, personalised, and high-quality items but do not want to spend an expensive cost. Additionally, when there are more options available, client expectations become more individualised. The production technology of additive manufacturing (AM) may offer one way to encounter these challenges (1) and it is often used in dentistry manufacturing (2-4)(2-6).

The AM often known as 3D printing is an alternative to subtractive manufacturing in the CAM step of the dental digital workflow, that is capable of generating devices by layering materials using a computer-generated design file in standard tessellation language (STL)(7). Following the rapid progress of AM of polymers and metals, advances in this approach applied to ceramic materials have gained popularity in recent years (4, 7-9). Although research into ceramic 3D printing began in the 1990s, its industrial use is still limited when compared to polymers and metals and the adoption of ceramic additive manufacturing is dependent on technology availability (10).

The potential of AM to enable the cost-effective manufacturing of prototypes, low-volume products, and even single customised pieces without the necessity of expensive specialised mould tooling is its first immediately apparent benefit for the industry (11). In the context of AM, changing the design of a component is as simple as updating the corresponding digital design files, which can involve a change in build orientation and optimization of processing parameters but does not require any physical modifications to the machine or custom tooling. The overall production cost of AM technologies is thus somewhat independent of design complexity (12) and is rather related to material utilisation (i.e. cost of materials and build size), machine power consumption, labour cost and depends on the number of parts to be produced (13).

Furthermore, the absence of bespoke tooling translates not only into cost savings but also into substantially shorter prototyping and production lead times. Another key advantage of AM is the inherent design freedom provided by layer-wise part formation, which allows for the fabrication of items with great geometrical complexity that would be difficult, if not impossible, to produce using subtractive or formative manufacturing procedures. This improved design freedom provided by AM also facilitates the reduction, or even elimination, of extra forming, cutting, and assembly operations, leading to shorter lead times and cheaper manufacturing costs (13).

Among several available AM fabrication techniques, this study focuses on the Shell Sintering Technology (SST), which is based on a fused filament to create a negative mould, allowing dental prosthesis manufacturing. Taking advantage of all the benefits of AM, the economic model of this novel technique must be studied, making it possible to determine several scenarios and apply economic modelling concepts to compare it to traditional methods.

Traditional and CAD/CAM casting are two of the most common methods used by dentists to make dental prostheses. Both techniques require a full understanding of the materials, tools, and manual operations in order to produce a high-quality prosthesis. This well-known lost wax casting technique is still utilised as a reference comparison standard for alternative production technologies due to its historical significance.

The costs of the products can be easily determined, and the evaluation's findings will provide industry decision-makers with a useful foundation for making decisions about whether to invest in a particular technology. This represents a significant step forward for a new service.

Accordingly, this article studies production components to identify the impact of dental production elements such as material, labour, and machinery and gives data on how producers of dental prostheses could boost output to meet rising demand using these technologies. In order to address any anticipated changes in demand in the dental industry, it is hoped that this comparison of the traditional methods and SST will emphasise the advantages of each process and help all professionals make an informed decision for their business.

MATERIALS AND METHOD

Technical principles

SST

Shell Sintering Technology (SST) is a novel production technology for dental prostheses based on $ZrSiO_4$-glass composite. This technique uses AM to create a collapsible $ZrSiO_4$ negative mould of a crown or bridge using fused filament fabrication (FFF). The FFF-based AM can fabricate objects with significant amounts of ceramic and metallic material (10, 14-19) and this method is therefore appropriate for creating collapsible moulds made of metal or ceramic that can withstand high temperatures.

The glass powder is used to fill the mold's negative cavity and then sintered. After the parts have been heated to debinding the negative structure, sintered crowns, bridges, copings, and dentures are produced. This idea has been demonstrated to be effective and opens up a new opportunity for fabricating glass-ceramic materials using AM techniques and a collapsible ceramic mould (20). The schematic for this method is illustrated in Figure 1.

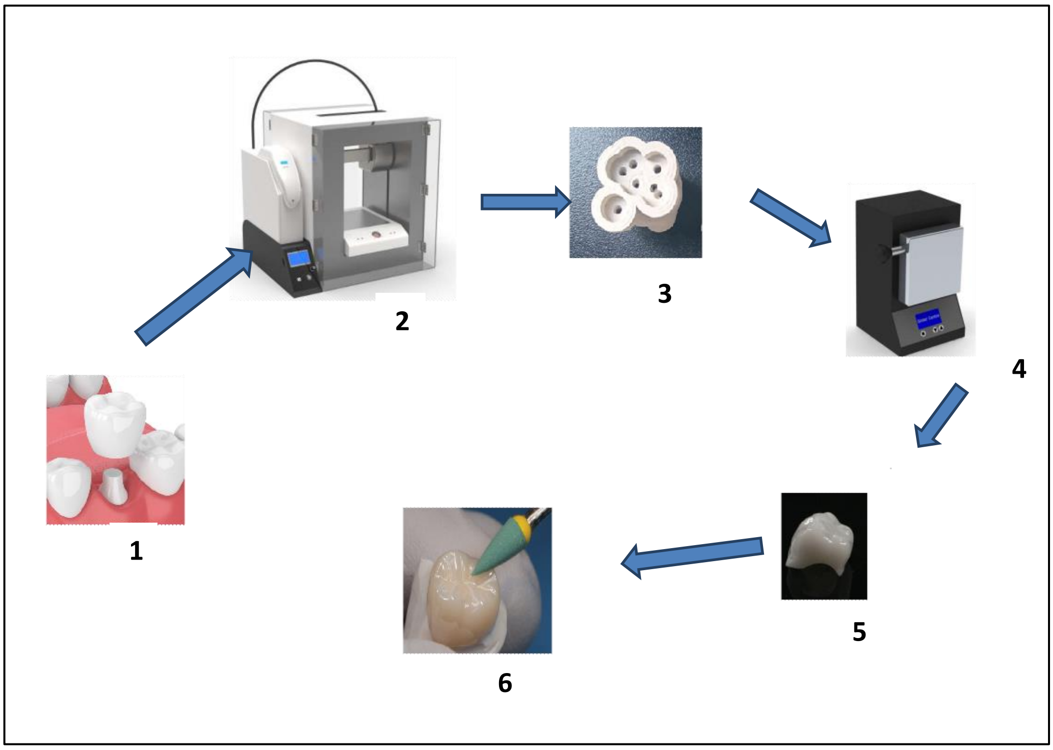

Figure 1: Schematic illustration for SST technology. Part (1) CAD design and adjustments, (2) 3D fabrication of negative mould, (3) filling the mould with porcelain powder, (4) sintering, (5) sinterized dental crown, (6) finishing with make-up, if necessary.

Traditional Lost Wax Casting (Hotpress)

Making a wax model of the needed restoration and casting it in a heat-resistant ceramic material is known as lost wax casting. Wax is used to create the patterns because it is easily manipulated, precisely moulded, and can be fully removed from the mould by heating (21, 22).

A high-temperature furnace is used to heat the invested pattern, forcing all wax patterns to burn off and leave a hole that will subsequently be filled with the desired molten metal or ceramic using hotpress technique. The manual creation of high-quality dental wax patterns depends on the expertise of skilled craftspeople and it is a laborious process. During the manual production operation, removing the wax pattern from the die may cause pattern enlargement, and because the wax is glossy, minor errors may be difficult to detect (23).

Hotpress technology is employed in dentistry for over 40 years to construct single crowns and partial fixed dental prostheses by simultaneously applying heat and pressure to prefabricated ingots in a previously invested mould cavity. Depending on their use and the patient's aesthetic preferences, ceramics can be pressed onto a substrate or created as a monolithic restoration (24, 25).

This traditional approach of manually building the model in wax and then employing the process to fill the mould will be referred to as the hotpress technique in this study.

CAD/CAM Casting

The most crucial and labor-intensive phase in producing the porcelain-fused-to-metal crown, pressed ceramic crown, and framework is the creation of the wax pattern, although it is possible to use a new approach for automated wax-up production. It is feasible to generate wax patterns produced from castable materials and avoid numerous limitations of traditional wax-up procedures by introducing alternative CAD/CAM technologies. The use of CAD/CAM systems has several benefits, including the ability to produce restorations of a higher and more uniform quality using blocks of wax that have been commercially formed, the standardisation of the shaping of restorations, and the reduction of production costs, labour, and time (21).

Using CAD/CAM technology, the wax pattern is created by milling a commercial wax block. Following that, the investment and hotpress processes are carried out in the same manner as in traditional casting.

In this study, the approach of building a wax model by machine and subsequently filling the mould by hotpress will be referred to as CAD/CAM Casting.

Economic Model Development

The part cost (C_{part}) is the sum of direct and indirect costs (1, 26) as indicated by Equation I and were examined: direct cost (C_{direct}), machine cost ($C_{machine}$), and labour cost (C_{labour}), excluding administrative overhead:

$$C_{part} = C_{direct} + C_{machine} + C_{labour} \quad \text{(I)}$$

Other economic models for various types of dental prostheses can be built using overhead parameters. In this study, we are looking at the inputs for producing a porcelain dental crown, however, this may also be used to create bridges, as shown in Table 1. It is important to keep in mind that a bridge takes longer to manufacture than a crown, and the economic model must be revised to reflect this.

We worked with material and equipment suppliers to gather information on the process steps and commercial production operation's needs, and a comprehensive list of inputs for each of the three techniques is presented in Table 2. For a cost comparison and predicting overhead parameters, deterministic bottom-up economic models were built using all the inputs shown in Tables 1 and 2.

Table 1: Prostheses Parameters.

Type	Mass (g)	Laboratory Price	Sintering batch
Crown	0.5	100	10
Bridge 2x2	1	200	5
Bridge 3x2	1.5	300	3

Table 2: Economic parameters for all studied techniques

Parameter	SST	Hotpress	CAD/CAM Casting
Daily Journey (h)	14	14	14
Clabour (US$/h)	12	12	12
Waste ratio (%)	5	15	10
Amortization Time (years)	2	2	2
CNC/SST Equipment Cost (US$)	20000	-	67420
Extra Kiln Furnace Cost (US$)	1200	2000	2000
Benchtop 3D Scanner Cost (US$)	10000	-	10000
Extra Hot Press Furnace Cost (US$)	-	2000	2000
N_{months}	12	12	12
$N_{worksays}$	20	20	20
$C_{part/g}$	12.90	36.20	36.20
M_{part} (g)	0.5	0.5	0.5
N_{batch} (parts)	10	10	10
$N_{labour\_journey}$ (h)	8	8	8
$N_{overhead}$ (h)	14	14	14
Price (US$)	100	100	100

Direct Cost – Material

The direct cost is related to the material used to construct the part and also any waste generated during the process. In this study, porcelain powder is used to investigate dental crown fabrication for SST and porcelain ingots for hotpress and CAD/CAM casting:

$$C_{direct} = C_{material} + C_{waste} \quad \text{(II)}$$

$$C_{material} = M_{part} \cdot C_{part/g} \quad \text{(III)}$$

$$C_{waste} = \% \, . C_{material} \quad \text{(IV)}$$

Where M_{part} is the mass used to fabricate the part, $C_{part/g}$ is the material cost per grams and C_{waste} is the material waste cost. All these values were obtained from Table 2. It must be noted that the amount of waste produced and the material cost per grams differ, based on the technology.

Indirect Cost – Machine

The machine cost was calculated through quotations, and it is the total cost of all machines used in the process, divided by the number of parts manufactured over a two-year payback period. It is important to mention that the number of machines varies by technology and is proportional to the amount of time spent in each stage. There is a fundamental equipment arrangement for each technology. For example, the hotpress process requires only two pieces of equipment (one kiln furnace and a hotpress), but CAD/CAM casting requires four pieces of equipment (3D Scanner, CNC, kiln furnace, and hotpress).

$$C_{machinehotpress} = C_{kilnfurnace} + C_{hotpress} \quad \text{(V)}$$

$$C_{machineCAD/CAM} = C_{CNC} + C_{3Dscanner} + C_{kilnfurnace} + C_{hotpress}$$

(VI)

SST technology, on the other hand, basically requires three pieces of equipment (3D scanner, SST printer and kiln furnace):

$$C_{machineSST} = C_{SST} + C_{3Dscanner} + C_{kilnfurnace} \qquad \text{(VII)}$$

As demand grows, so will the requirement for specialised equipment due to the additional hours necessary for production. As a result, the model must take into account the costs of the new equipment.

$$C_{machine} = \frac{\sum C_{equipment} \cdot N_{equipment}}{N_{workdays} \cdot t_{amortization} \cdot N_{months}} \qquad \text{(VIII)}$$

Each technique takes a different amount of time to complete a part. Knowing every step of the process is essential for calculating the machine cost per part since it allows you to determine the machine time spent on each batch, and this information is shown in **Table 3**. With this knowledge, we can also determine how many machines are required to satisfy a particular demand:

$$N_{machine} = round_{up}\left(\frac{t_{machine} \cdot P_{daily+waste}}{N_{overhead}}\right) \qquad \text{(IX)}$$

where $P_{daily+waste}$ is calculated as:

$$P_{daily+waste} = round_{up}\left(P_{daily} \cdot (1 + \%waste)\right) \qquad \text{(X)}$$

Finally, the cost machine per part related to daily production can be calculated, where P_{daily}ranges from 1 to 100 parts on daily basis:

$$C_{machine\_part} = C_{machine} / P_{daily} \qquad \text{(XI)}$$

Indirect Cost – Labour

The labour cost is equivalent to the overhead cost in this study because we excluded the low-cost energy and maintenance costs due to a lack of information. It is also necessary to calculate the number of workers as demand grows:

$$C_{labour} = N_{tech} \cdot C_{labour/h} \cdot N_{labour\_journey} / P_{daily} \qquad \text{(XII)}$$

Where P_{daily}ranges from 1 to 100 parts on daily basis.

$$N_{tech} = round_{up}\left(\frac{t_{manual} \cdot P_{daily+waste}}{N_{overhead}}\right) \qquad \text{(XIII)}$$

Table 3: Process steps and time process for all studied techniques

Process Step	SST	Hotpress	CAD/CAM casting
1	Aquire 3D model Process Time: 0.5h	Manual molding Process Time: 1h	Aquire 3D model Process Time: 0.5h
2	Modify and Design Process Time: 0.33h	Ceramic Molding Process Time: 1h	Modify and Design Process Time: 0.33h
3	Fabrication Process Time: 0.5h	Wax Modeling Process Time: 2h	CNC Step Process Time: 0.5h
4	-x-	Tree Assembly	Tree Assembly

5	-x-	Mold Form Process Time: 0.67 h	Mold Form Process Time: 0.67 h
6	-x-	Wax burn Process Time: 1.92 h	Wax burn Process Time: 1.92 h
7	Sintering Process Time: 6 h	Hot Press Process Time: 1 h	Hot Press Process Time: 1 h
8	-x-	Sand Blasting Process Time: 0.67 h	Sand Blasting Process Time: 0.67 h
9	Make-up Process Time: 1.25 h	Make-up Process Time: 1 h	Make-up Process Time: 1 h
Process and Equipment Time			
Total Lead Time (h)	8.58	9.33	6.67
Tmanual (h)	2.13	5.38	3.47
TmachineSST (h)	0.48	-x-	-x-
TmachineCNC (h)	-x-	-x-	0.42
Tmachine3Dscanner (h)	0.50	-x-	0.50
Tmachinefurnace (h)	6.00	1.92	1.92
Tmachinehotpress (h)	-x-	1.00	1.00

Overhead Data

To gather important data and compare the three approaches mentioned in this study, a variety of production metrics must be calculated. The relevant overhead information is shown in equations XIV through XIX, and it comprises annual production, annual overhead, revenue, profit, payback, and return on investment (ROI). With the help of all of this crucial data, it is possible to fairly evaluate and contrast the three techniques:

Annual Production:

$$P_{annual} = P_{daily} .\ N_{workdays} .\ N_{months} \qquad \text{(XIV)}$$

Annual Overhead Cost:

$$C_{annual\_overhead} = C_{part} .\ P_{annual} \qquad \text{(XV)}$$

Annual Revenue:

$$R_{annual} = Price \ .\ P_{annual} \qquad \text{(XVI)}$$

Annual Profit

$$Prof_{annual} = \left(Price - C_{part}\right) .\ P_{annual} \qquad \text{(XVII)}$$

We can state that there is a payback and return on investment only when there is an annual profit:

$$Payback = \frac{C_{annual\_overhead}}{Prof_{annual}} \qquad \text{(XVIII)}$$

Return on Investment:

$$ROI = \frac{Prof_{annual}}{C_{annual\_overhead}} \qquad \text{(XIX)}$$

RESULTS AND DISCUSSION

Direct Cost – Material

Figure 2 shows that the material cost for a part associated with the SST process is nearly 67% less than the cost associated with the other two techniques. This is because that SST may use porcelain powder for crown fabrication while others require block for hotpress. SST's material operating losses are also minimized, decreasing material costs per part.

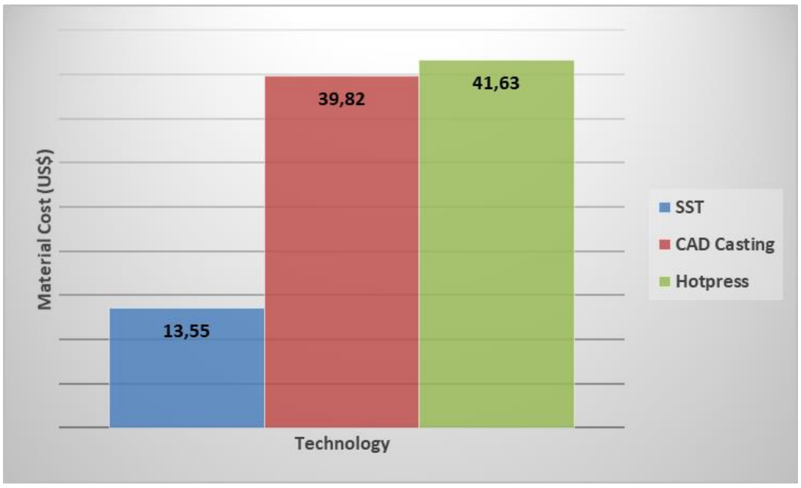

Figure 2: Material costs per manufactured part, based on the employed technology

Indirect Cost – Machine

As demand increases, equipment costs per manufactured part decrease until the moment it is necessary to buy a new machine, as shown in Figure 3. As expected, the traditional hotpress offers the lowest cost due to the low demand for equipment use and acquisition. In terms of equipment cost per part produced, the SST process is in the middle category and is 57% less costly than CAD/CAM casting, calculated from the average of the values presented in the small graphic inside Figure 3.

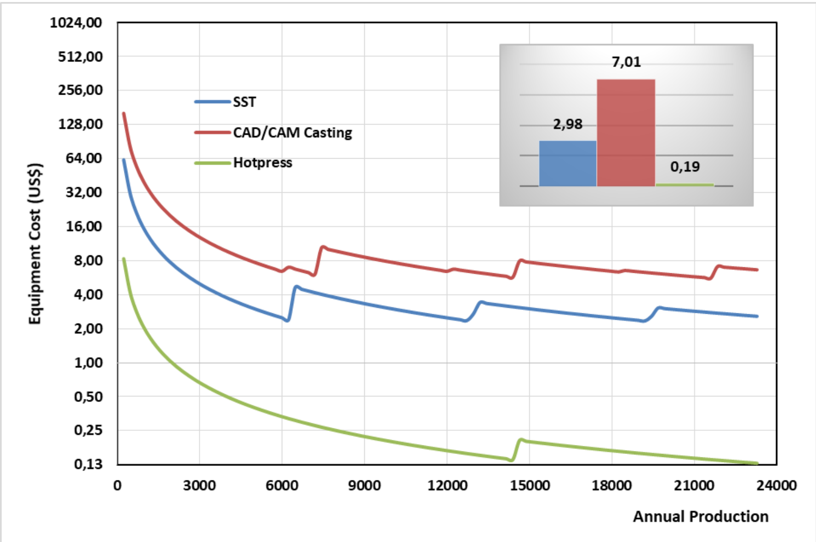

Figure 3: **Equipment cost per manufactured part as growing demand.**

Indirect Cost – Labour

Figure 4 illustrates the increasing requirement for specialists as demand grows. It can be evaluated that the hotpress requires more staff than other technologies. As production increases, the monthly salary expense increases, as shown in Figure 5, and has a significant impact on the final cost of manufacturing the parts, shown in Figure 6. In this example, SST technology has the lowest cost, with a 64% drop in the number of technicians when compared to the hotpress process and 43% when compared to the CAD/CAM casting technique.

Figure 6 shows that the relative labour costs for the three techniques remain nearly constant when production increases. It is possible to assume that employing the SST process will result in lower labour costs for producing crowns approximately 62% less expensive than using the hotpress method and 40% less expensive than using CAD/CAM casting. Figure 7 compares the techniques in terms of all expenses involved, and it can be observed that the SST process has the lowest material and labour costs, while hotpress has the lowest equipment cost.

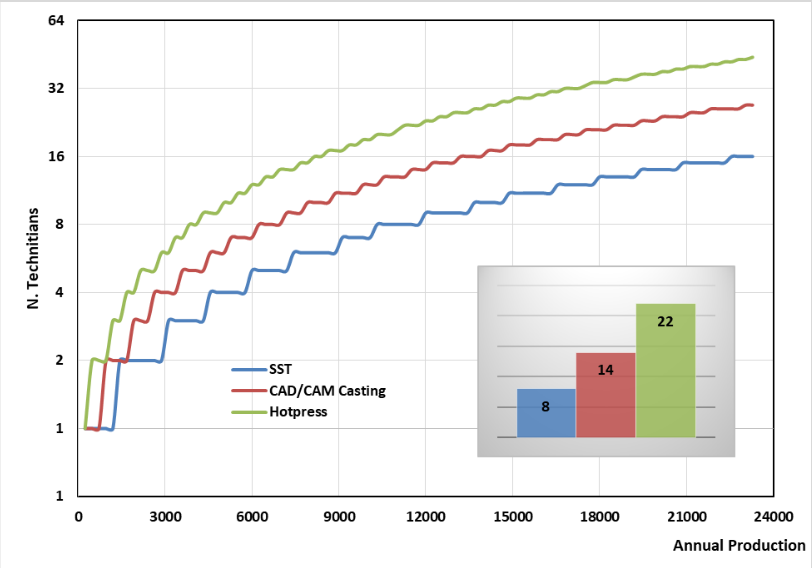

Figure 4: The number of workers necessary for each technique in a simulated growing demand.

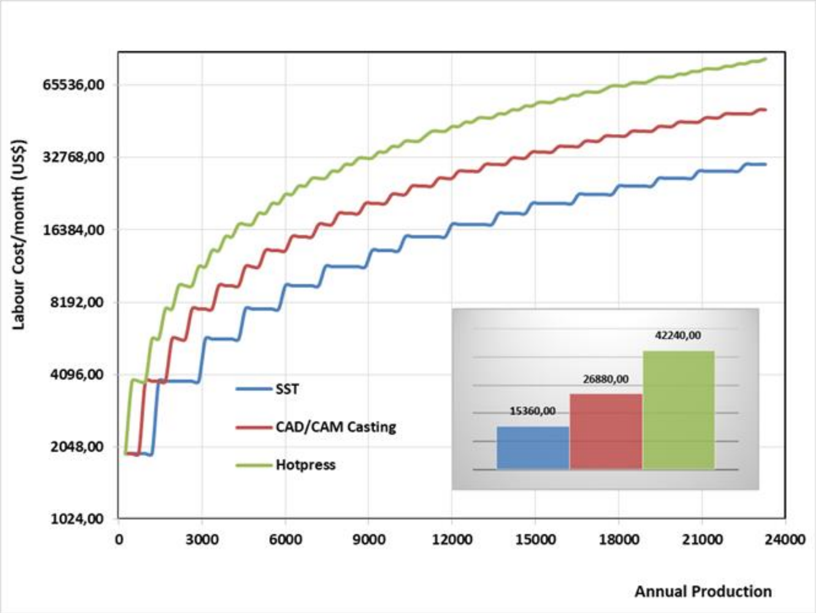

Figure 5: **Labour cost per month for simulated growing demand.**

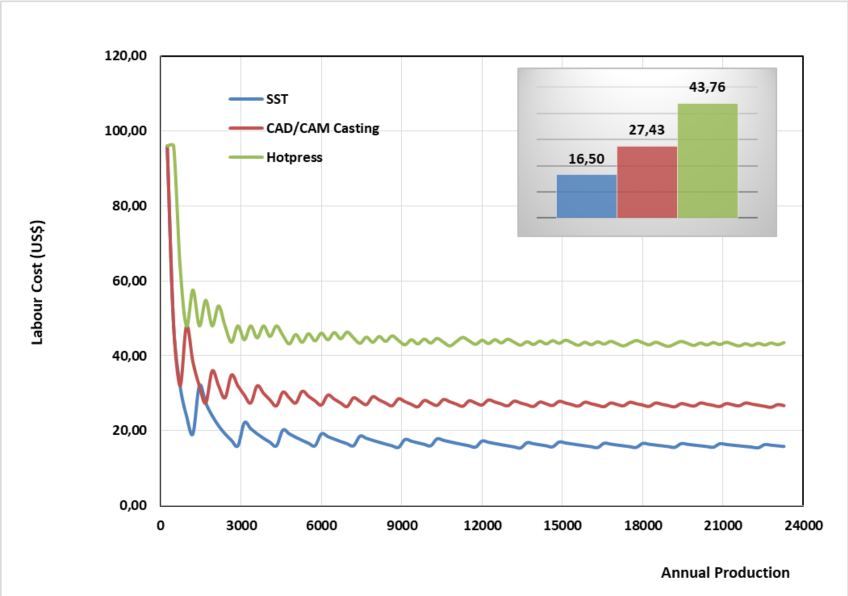

Figure 6: **Labour cost per part as demand increases.**

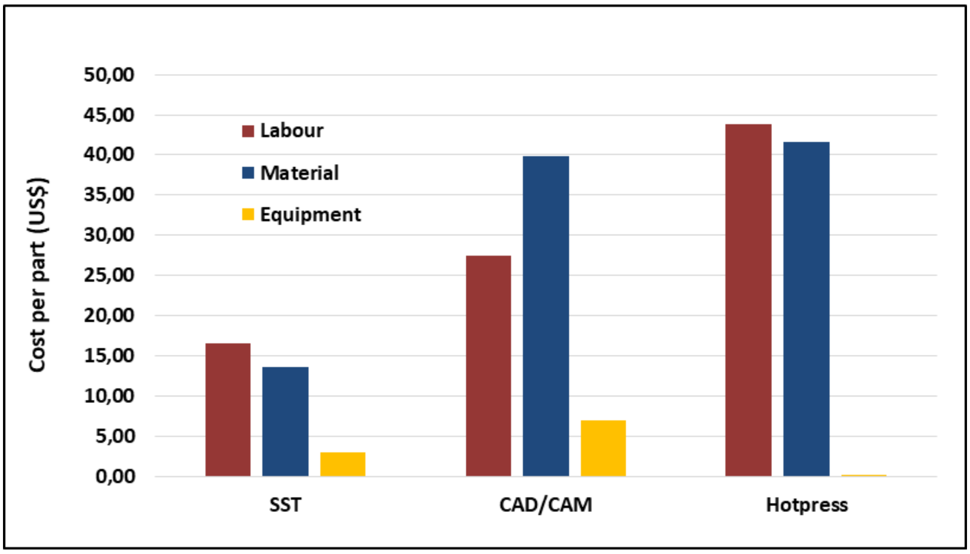

Figure 7: **Cost comparisons of the technologies under study.**

Labour, material, and equipment expenses contribute to a low total cost for SST, as shown in the figure below, averaging US$35.00 after increasing demand by 12 crowns per day (see Figure 11 ahead for more details).

As shown in Figure 9, the material has a considerable impact on the CAD/CAM casting process, accounting for roughly 53.6% of expenses, followed by the cost of work (36.9%), and equipment (near to 9.4%).

In terms of the hotpress method, we discovered that the cost of labour is roughly 51.1%, followed by the cost of material at 48.6%, and with a tiny cost of 0.2% associated with equipment, as shown in Figure 10.

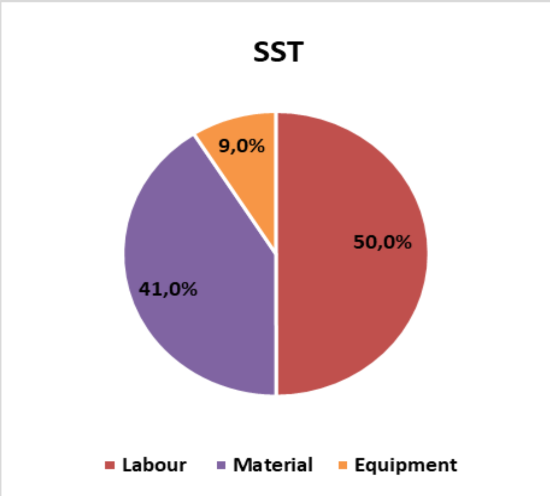

Figure 8: Cost summary for SST technology.

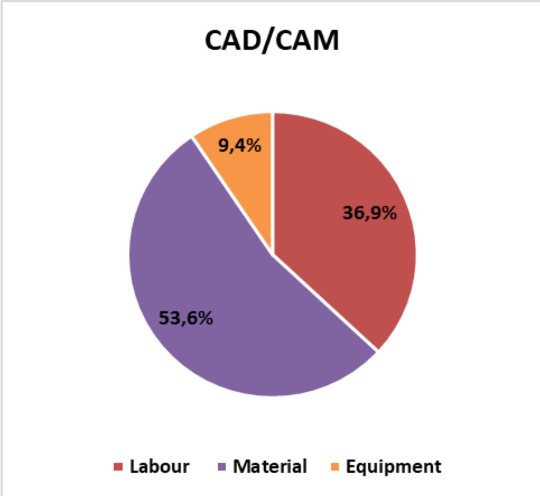

Figure 9: Cost summary for CAD/CAM Casting technology.

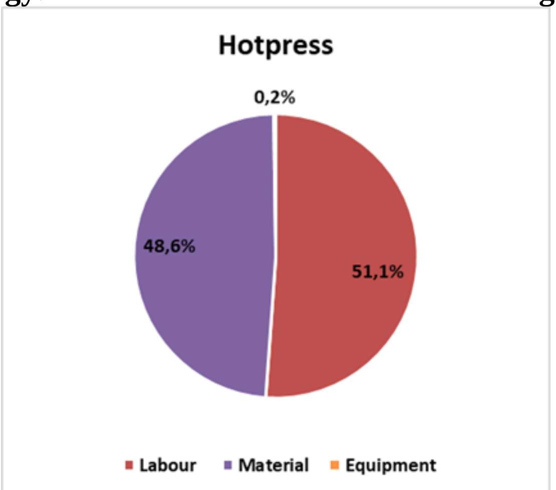

Figure 10: **Cost summary for Hotpress technology.**

Overhead Data

The cost of manufacturing a product can then be determined based on demand by adding up all other previously determined costs and using equation 1. Once the cost per part has been determined, we can calculate the other crucial variables for analyzing the production process. By analysing Figure 11, it is possible to conclude that the traditional hotpress has the highest cost for producing a crown (considering material, labour and machine), followed by

CAD/CAM, which has a roughly 13.0% lower cost, and then the SST, which has the lowest cost, inferior to the other two approaches by an average of 61.0%. Another significant point to note in this figure is that the cost is reasonable for the SST and hotpress methods when production is relatively low.

The annual manufacturing costs are shown in Figure 12, where production costs are comparable, with a 13.0% difference between hotpress and Cad/CAM processes. The cost of manufacturing a crown in the SST process is reduced by up to 60.0% when compared to the most extensive process, which in this case is the hotpress.

The lower the production cost, the higher the profit obtained. As a result, the SST process inevitably generates more revenue than the other techniques as shown in Figure 13. When compared to CAD/CAM casting, SST is 60.0% more profitable, and when compared to the hotpress, it is 78.0% more cost-effective.

The SST method is expected to have a shorter payback period than other technologies, due to its values of lower manufacturing costs and increased profitability. As shown in Figure 14, the average payback period for SST is 0.5 years, compared to 2.9 years for CAD/CAM casting and 5.9 years for traditional hotpress. As a result, investment in SST Technology becomes extremely attractive. Figure 15 shows that hotpress technique has a ROI of about 17.0%, while the CAD/CAM casting technique has a ROI that almost doubles with increasing demand. However, the ROI for the SST technique is highly expressive, reaching levels of 187.0 %.

This suggests that SST technology, serving as a new front in the production of ceramic parts, can improve the entire prosthesis production chain while having low operating costs and great profitability.

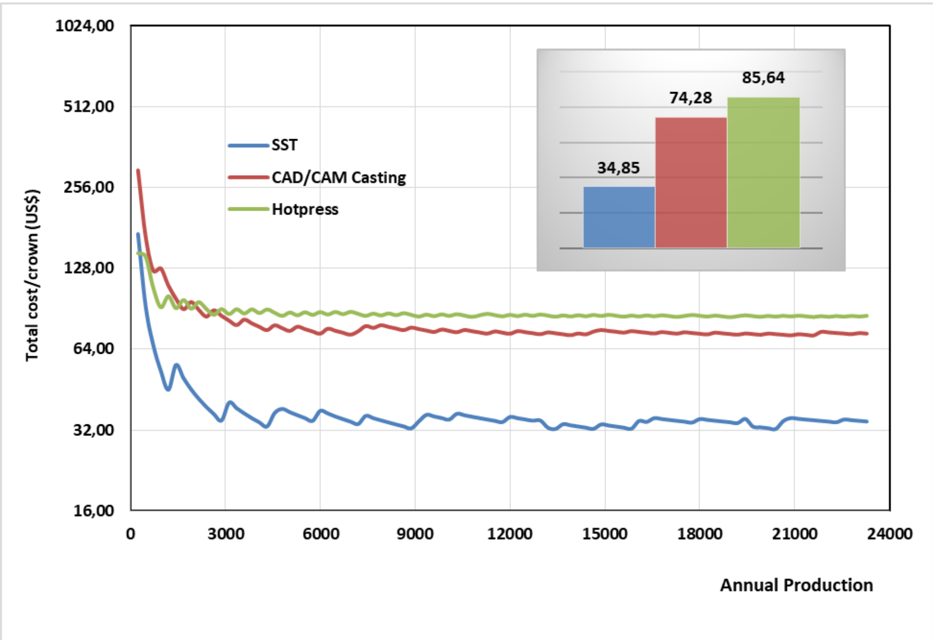

Figure 11: **Total cost per dental crown based on an increase in production.**

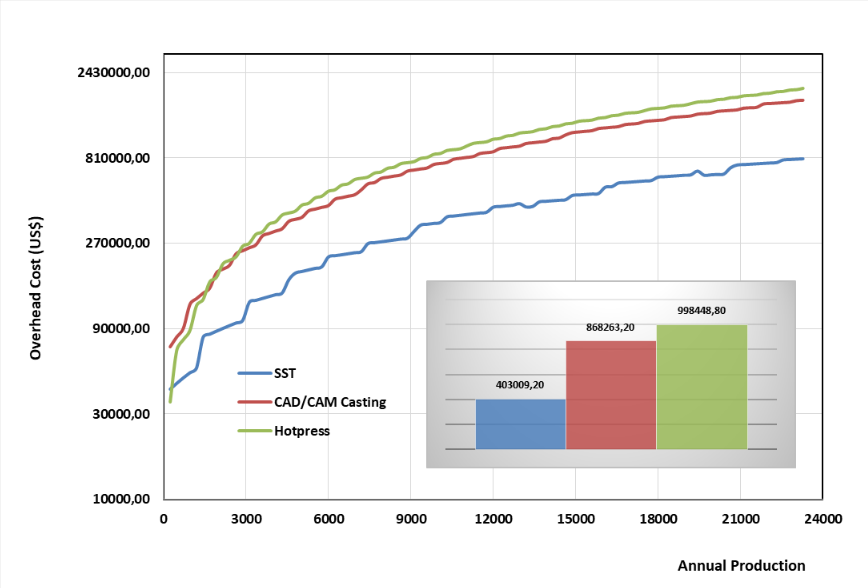

Figure 12: **Total overhead cost in a simulated increasing production.**

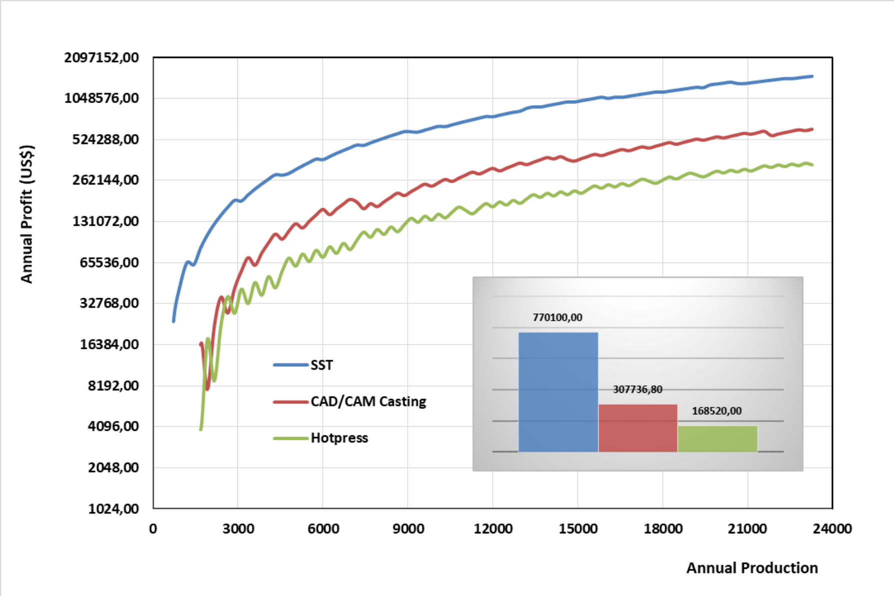

Figure 13: **Annual profit as demand rises.**

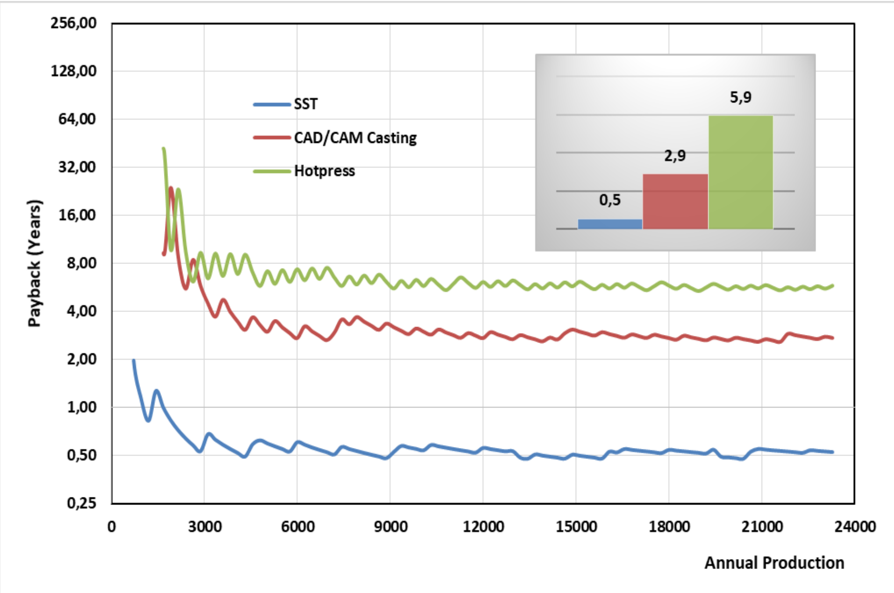

Figure 14: The payback period for the studied technologies.

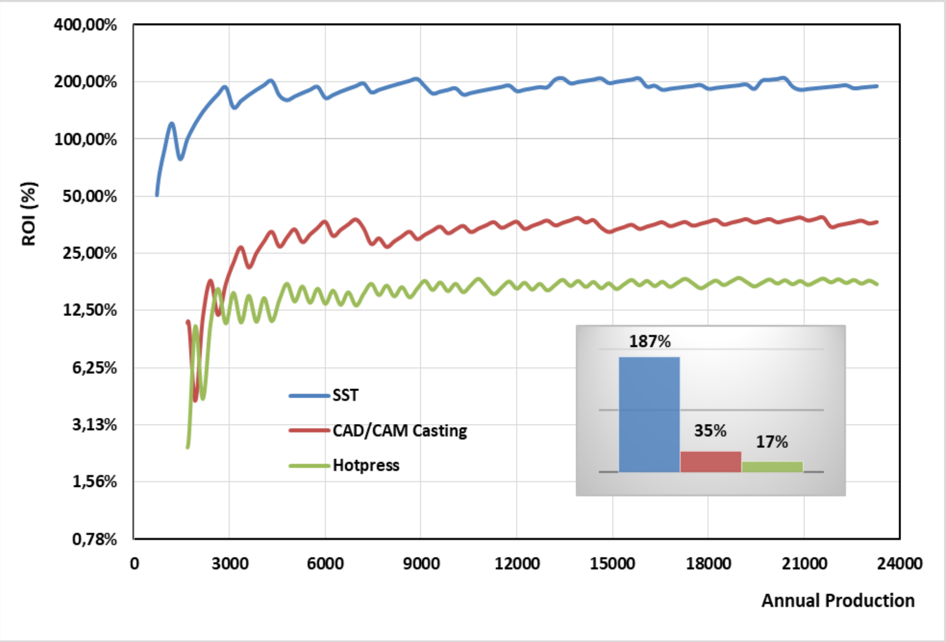

Figure 15: **Return on Investment for the three studied techniques.**

Table 4 provides a general summary of the economic model's outputs. It is important to keep in mind that the data are not uniform, especially at the beginning of the processes, where there are no values, as in the case of payback, or have negative values, as in annual profit and ROI. In this scenario, we choose to evaluate the medians of each case in order to establish a more trustworthy data comparison.

Table 4: Summary of economic model´s output for all studied techniques.

Technology	**Material Cost***	**MachineCost***	**N Tech**	**Labour month***	**Labour Cost***
SST	13.55	2.98	8	15360.00	16.50
CAD/CAM Casting	39.82	7.01	14	26880.00	27.43
Hotpress	41.63	0.19	22	42240.00	43.76
Technology	Total Cost/part*	Overhead Cost*	Annual Profit*	Payback (years)	ROI (%)
SST	34.85	403009.20	770100.00	0.5	187
CAD/CAM Casting	74.28	868263.20	307736.80	2.9	35
Hotpress	85.64	998448.80	168520.00	5.9	17

Note: * values in US$.

CONCLUSION

Deterministic bottom-up economic models served as a representation for hotpress, CAD/CAM casting, and SST processes in this investigation. These models were used to calculate crucial factors for assessing each technique's productivity and profitability. Some publications discuss the economics of dental prosthetic processes, frequently with the help of other economic models and practical applications (27, 28). Some generalist works to place a focus on additive manufacturing (29-32) and is the basis for applications in a variety of fields. As the first to emphasize the primary production procedures of the most widely used dental prosthesis, the information offered in this article constitutes an important contribution.

The results showed that the SST technique has reduced material and labour costs for the manufacturing of dental crowns, whereas the hotpress method's equipment costs are lower compared to the other two methods. Although the hotpress technique has a low equipment cost, this benefit has been decreased because of the longer lead time compared to the other techniques, therefore labour costs rise due to higher labour demand. The hotpress process had the two highest labour and material production costs per part. As a consequence, when compared to SST and CAD/CAM casting, this process has the highest production cost. When comparing the three techniques, the CAD/CAM casting process ranked second due to material and labour costs.

Despite the high material and equipment acquisition costs, the CAD/CAM casting process provided a ROI of 35.0%, with an average payback duration of 2.9 years, as compared to the hotpress method, which had a payback period of 5.9 years and a ROI of 17.0%.

Although these values are quite acceptable in terms of economics, the SST technique demonstrated extremely advantageous values for low and large-scale processing of dental crowns, reaching above 180% ROI with a payback of 0.5 years. Even with an intermediate lead time, SST has very favourable economics and the potential to transform the dental prosthesis manufacturing market.

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