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Productive efficiency and its determinants in the Finnish Public Dental Service

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Abstract – *Objective:* Our objective was to investigate the cost efficiency of the Public Dental Service (PDS), which, until 2000, was responsible for organising dental care for children and younger adults born in 1956 and later. *Methods:* Input and output data and information on various organisational and environmental characteristics were collected from 228 municipal PDS units in Finland. First, non-parametric data envelopment analysis (DEA) was employed to assess efficiency. In the second stage, econometric Tobit analysis was used to explore various predictors of cost efficiency, technical efficiency and allocative efficiency. As input in the DEA model we used personnel full-time equivalents and material and other costs expressed in monetary terms, and as output we used the number of treated patients. *Results:* The study showed big differences in cost efficiency between the PDS units studied. The average cost inefficiency was 30%. Approximately two-thirds of the observed cost inefficiency was because of technical inefficiency and one-third because of allocative inefficiency. High state-subsidy levels, and a high proportion of young patients predicted inefficiency, and young population and low socioeconomic conditions in the municipality predicted efficiency. The results also indicated that many PDS units could have improved allocative efficiency by increasing the relative numbers of auxiliaries in relation to dentists. On the other hand, some units were too small to employ full-time dental hygienists efficiently. *Conclusions:* In the Finnish PDS, there are uncommitted resources that could be reallocated so as to improve overall efficiency.

Key words: data envelopment analysis (DEA); determinants of efficiency; productivity; Public Dental Service

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Health economic studies on dentistry in Northern Europe have largely concentrated on areas like equity in access and utilisation of services (1), supplier induced demand (2, 3) and, to some extent, workforce planning (4). However, economic evaluations of system performance in oral health care have been scarce (5). In public oral health care delivery systems with limited budgets and unlimited demands, choices have to be made between different responses. An understanding of economic evaluation is important for the purchasers as well as providers and financiers of services, especially when reforms in care delivery systems are to be made. The performance of the public oral health care systems has been recently evaluated in Norway and UK (6, 7).

In Finland, a tax-financed Public Dental Service (PDS), administered and run by local municipalities alone or in co-operation and supervised by the Ministry of Health and Welfare, was established in early 1970s as part of a primary health care reform. The aim of the PDS, consisting of 265 units (health centres), has been equitable distribution of dental services in a sparsely populated country (5.1 million inhabitants, land area 330 000 km^2). Until the year 2000, the first goal was to provide care for children and younger adults – according to the statutes, those born in 1956 and later. The second, more informal aim has been to maximise the oral health of the 0–18 year olds. In practice, in rural areas (with no private practitioners) the whole population has been able to use public services, whereas the largest cities, with high numbers of private practitioners, have often restricted access to age groups even younger than stipulated in the statutes. When the study was performed, the public sector employed slightly fewer than half and the private sector slightly more than half of active dentists. The public sector catered for practically all children and youngsters and half of the adults who used dentists' services.

Although the Finnish PDS has been operating for almost 30 years, economic evaluations of the system have been few. In a seminal study, Sintonen compared productivity of private and public dentistry using an econometric model (8). In the early 1980s, big differences were found in the productivity of randomly selected municipal PDS units, indicating that high governmental subsidies were associated with low productivity (9). A long-term productivity analysis of a representative sample of the PDS units revealed that the productivity, measured using the number of patient visit as output, decreased by 45% between 1982 and 1991 (10).

Routine reports on output and costs of the PDS for local decision makers have been published every 3 years since 1991. According to the 1997 report, the total running expenses of the PDS per inhabitant in the local municipalities varied between EUR 29 and EUR 95, the mean being EUR 45 (11). The annual numbers of patients seen by one dentist varied between 600 and 1400 (means of health centres, not individual means) in the different PDS units; the mean was 900 per year. About 25% of the running costs of the PDS was paid by the state, about 20% was collected from adult patients as fees and the rest was paid through municipal taxes. All dental care including orthodontics was free of charge for children under 19 years of age. Patient fees for adults were set by the government and did not aim to cover the production costs of the services. However, in health centres where the share of adult patients was large, the patients' payments may have covered as much as 40% of the running costs (11).

Aim

The aim of this study was to investigate cost efficiency and its determinants in the Finnish PDS. We sought to explore cost efficiency more closely in each PDS unit by dividing efficiency into two components: technical efficiency and allocative efficiency. A two-stage procedure was used: efficiency scores (cost, technical and allocative) were first calculated for each unit, and these scores were then explained using a variety of factors expected to affect the observed inefficiencies. These factors included various organisational, institutional and environmental features of the PDS units.

Materials

Input and output variables

Data on the number of patients and the number of dental visits in various age categories, on workforce full-time equivalents, on costs for personnel, materials and other spending as well as on patient income were collected from all the 265 PDS units in 1997 as part of a special survey. Complete data were received from 228 municipalities, giving a response rate of 86%. Input variables were constructed by calculating the total consumption of materials and equipment in monetary units, and full-time equivalents in four employee categories: (i) dentists; (ii) hygienists; (iii) dental assistants; and (iv) others (e.g. receptionists and persons who sterilize instruments). As there was some variation in how the health centres recorded their staff in the registers, we minimised the risk of misclassification by combining the four employee input categories into three input variables: dentists, hygienists and other employees. As output variables we used the number of treated patients in three age categories: 0–18 year olds; 19–41 year olds; and over 41 year olds.

In our cost efficiency model, the price of the three staff categories was set by using official Finnish salary statistics. In Finland, wages are centrally negotiated, and variation in wage levels between facilities is small. The price index vector used for staff was: dentists = 1.00; hygienists = 0.44; and others = 0.40.

Explanatory variables

We also collected a set of background characteristics on the PDS units and their environments (12). These included the amount of state subsidy per resident in the municipality, level of residents' education measured as the percentage of high-school graduates and an index of the need of health services measured as the proportion of the municipality's residents on disability pension. Using national statistics (12), it was also possible to derive the average tax revenue per resident, the unemployment rate, and an index relating to the per capita expenditure on basic private dental care in the municipality and the proportion of under 19 year olds in the local populations. The dental health of the patients was measured using an index that gave the average number of decayed, missing or filled teeth per person (DMFT) in the age group 6–18 years.

The variation in the PDS units decisions about input allocations was measured in terms of the ratio of dentist full-time equivalents to other full-time equivalents and the ratio of dental hygienists to dentists. To take into account the variation in resource consumption in the younger patient groups, the proportion of 0–18 year olds in the total patient output was included in the explanatory variables. The effect of splitting an individual's treatment episodes into several separate visits was accounted for by measuring the average number of visits per patient.

Methods

First, non-parametric data envelopment analysis (DEA) was employed to assess technical efficiency. In the second stage, econometric Tobit analysis was used to explore various predictors of cost efficiency (CE), technical efficiency (TE) and allocative efficiency (AE). DEA is a non-parametric linear programming technique first introduced by Farrell (13) and later developed by Charnes et al. (14). DEA is based on relative efficiency measures, and in this framework, a PDS unit is judged to be efficient if it is operating on the best-practice production frontier. An example of the DEA efficiency definition is given in Fig. 1, which illustrates a simplified production technology of one output and two inputs. The shaded area in Fig. 1 indicates all the feasible combinations of inputs 1 and 2 to produce output 'y'. All units on the efficiency frontier (here, the south-west edge of the shade area) operate efficiently by producing the same output with minimal combinations of the two inputs. Units C and D are efficient and receive a technical efficiency (TE) score of 1. Unit A does not lie on the frontier and is technically inefficient (TE score is less than 1). The TE score for unit A is calculated by the ratio $\lambda = OF/OA$, which is directly related to unit A's distance from the efficient frontier. Unit A's input vector x^A can be contracted radially up to point F and still remain capable of producing output y.

Figure 1 can also be used to illustrate the determination of cost efficiency (CE). A cost-efficient mix of inputs requires that the slope of the production frontier coincides with the input price vector w' (relative wages and the price of materials). Unit D achieves both technical and cost efficiency because it uses both inputs optimally given their relative prices. Unit A could reach technical efficiency by reducing its use of inputs by $\lambda^A x^A$ (point F), but because of allocative inefficiency (measured by OE/OF), point F fails to minimise cost in the production of output 'y'. Overall cost efficiency can thus be divided into two components of allocative and technical efficiency. *Technical efficiency* measures how the levels of all the used inputs, given certain amount of outputs, compare with the optimal, best practice use of inputs. *Allocative efficiency* refers to the extent to which the input choices fail to satisfy the overall cost minimisation.

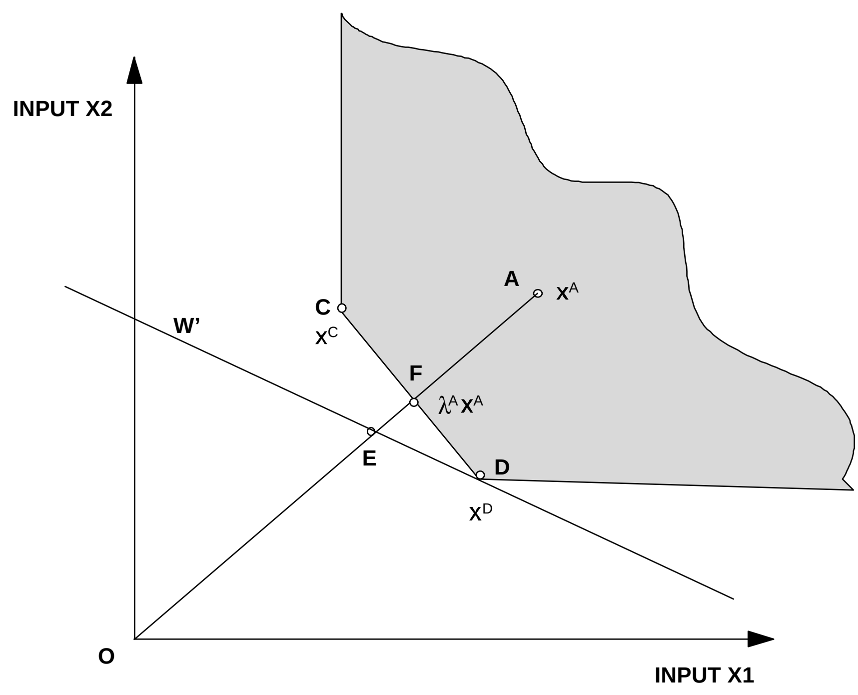

Fig. 1. Efficient frontier and efficiency measures in two-input, one-output case.

In applying DEA, TE and CE scores are first computed, and AE is then simply CE/TE. The mathematical notations for the computation of TE and CE are given in the Appendix. For the calculation of TE, CE and AE scores, we used the DEA specification of constant returns to scale. In all of our DEA models, three types of outputs: the number of treated 0–18 year olds, 19–41 year olds, and over 41 year olds were used. DEA models for TE and CE included four categories of inputs: full-time equivalents of dentists, hygienists and other employees, and the consumption of materials in monetary units.

The econometric model

In the second part of the study the estimated TE and CE scores were analysed by regressing them against a set of observed characteristics of the PDS units and their environments. For DEA scores, a censored Tobit model was used in the analysis (15), since both CE and TE scores take only non-negative values between zero and one. The efficiency scores (EFF = TE, AE, CE) were modified to describe the degree of inefficiency by setting INEFF = (1/EFF) − 1. In this case, the inefficiency scores are regressed, i.e. the negative sign of a coefficient means an association with efficiency, which allows it to be modelled by the following form:

$$\mathrm{INEFF}^* = \sum_j \beta_j \cdot x_j + v$$

$$\mathrm{INEFF} = 0 \qquad \text{if } \mathrm{INEFF}^* \leq 0$$

$$\mathrm{INEFF} = \mathrm{INEFF}^* \qquad \text{if } \mathrm{INNEF}^* > 0 \qquad (3)$$

where $\nu \sim \mathrm{N}(0, \sigma^2)$ and β_j are the parameters for explanatory variables x_j.

We used 12 explanatory variables in the Tobit analysis for explaining the difference in efficiency, using the efficiency scores of the different DEA models as the dependent variable.

Results

Cost efficiency

There were fairly big differences in CE between the PDS units in 1997. The average cost inefficiency was 30% (the average CE score was 0.70), which suggests that improving the CE of the PDS to observed maximum could reduce the costs by EUR 68 million.

The CE of the PDS units in the local communities varied between 0.31 and 1.0 on a scale where 0.0 means the lowest and 1.0 the highest efficiency. The 90th percentile of the CE distribution was 0.88, and the 10th percentile was 0.53 (Fig. 2). The most inefficient units were mostly found in rural areas with small populations. Of the units in the 10th percentile, 83% were PDS units with less than 10 000 inhabitants (the median population in Finnish municipalities was 11 000). However, small rural municipalities could be found also among the most efficient units. Generally, CE was not correlated with the size of the municipality, which means that the catchment areas for the health centres were mostly large enough to achieve scale efficiency.

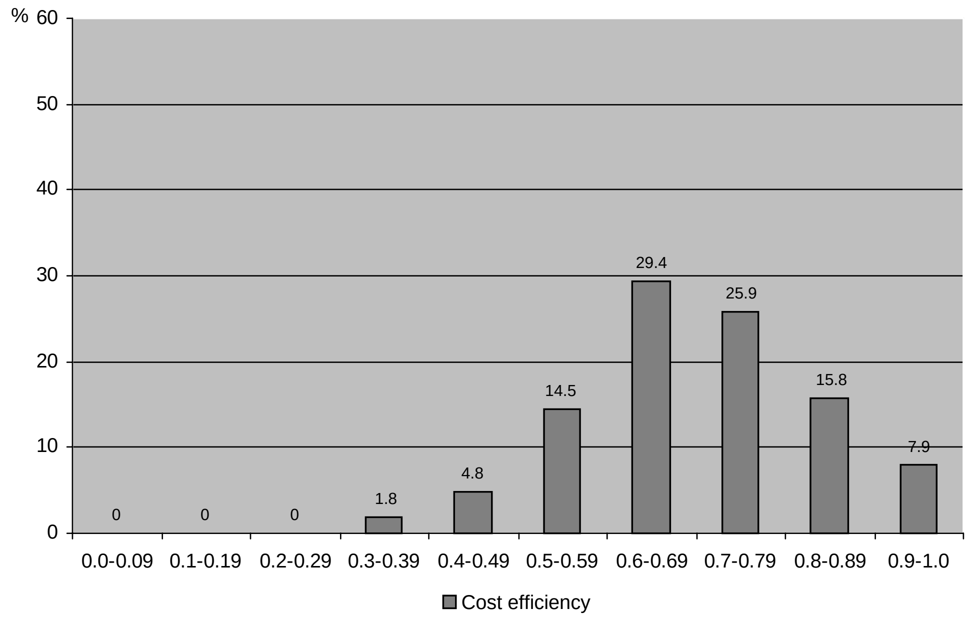

Fig. 2. Distribution of the municipal PDS units ($n = 228$) according to their cost-efficiency scores (%).

Table 1. Cost efficiency of PDSs in the 12 largest cities in Finland in 1997

City	Number of inhabitants in thousands	Cost efficiency	Technical efficiency	Allocative efficiency	Costs € Million	Optimal costs € Million
Espoo*	201	0.73	0.74	0.98	6.9	5.0
Helsinki*	539	0.78	0.90	0.87	18.7	14.5
Hämeenlinna	64	0.63	0.69	0.91	3.6	2.3
Jyväskylä	76	0.72	0.85	0.84	3.4	2.4
Kuopio	86	0.75	0.82	0.91	3.2	2.4
Lahti	96	0.96	1.00	0.96	3.4	3.3
Lappeenranta*	57	0.78	0.80	0.97	1.8	1.4
Oulu	114	0.76	1.00	0.76	4.3	3.3
Pori	77	0.72	0.77	0.94	2.7	2.0
Tampere	189	0.81	0.86	0.94	6.0	4.9
Turku	169	0.73	0.77	0.95	5.7	4.2
Vantaa	171	0.74	0.80	0.92	6.6	4.9

Dental services were provided to clients aged 0–41 years except in cities marked with * where the services were limited to younger age groups.

The CE scores of the 12 largest cities are presented in Table 1. The score for Espoo was 0.73, which means that the output produced in Espoo could have been produced using 27% less inputs (i.e. fewer dentists and other personnel) or alternatively Espoo should have been able to produce 27% more output using the existing resources. The example also shows that if the PDSs in the 12 largest cities worked as efficiently as the best units, a sum of EUR 15.9 million could have been allocated to treatment of older patients or to other purposes.

Technical and allocative efficiency

The results indicated big differences in TE and moderate differences in AE among the PDS units. Approximately two-thirds of the observed cost inefficiency was because of technical inefficiency and one-third because of allocative inefficiency (Fig. 3). The average level of TE was 0.78, and the average level of AE was 0.87. A significant number of the PDS units (43%) had only moderate TE (efficiency scores between 0.6 and 0.8) in their production. Only a minority of the units, 2.5%, operated very inefficiently (TE < 0.5; Fig. 3).

Sources of allocative inefficiency were studied using the solution to model (2) in the Appendix, which allowed comparison of each (observed, and TE adjusted) element of input vector individually to cost-minimising level of the corresponding input. According to the results, only 12.5% of the PDS units

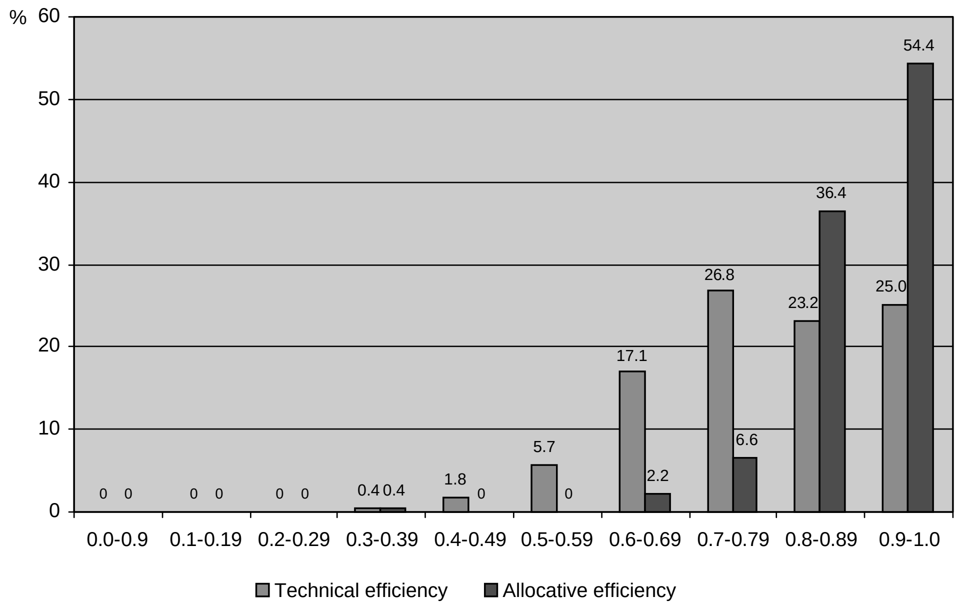

Fig. 3. Distribution of the municipal PDS units ($n = 228$) according to their technical and allocative efficiency scores (%).

Table 2. Tobit analysis using cost efficiency as the dependent variable

Predictor	Beta coefficient	*t*-ratio	*P*-value
Constant	−0.50		
Proportion of municipal residents with higher education	−0.23 E-02	−0.28	0.79
State subsidy per municipal resident	0.12 E-03	2.85	0.004
Tax revenue per resident (state + municipal)	−0.24 E-04	−1.61	0.11
Proportion of municipal residents on disability pension	−0.40 E-02	−2.5	0.01
Proportion of unemployed in the municipality	0.58 E-02	0.99	0.32
Per capita expenditure on state-subsidised private dental care in the municipality	−0.24 E-02	−2.37	0.02
Proportion of dentists to other staff	0.90 E-01	0.60	0.55
Number of dental visits per person	0.19	7.12	0.000
Proportion of patients aged 0–18 years	0.18	3.95	0.000
DMFT mean in 6–18 year olds	0.77 E-02	0.23	0.82
Proportion of hygienists to dentists	0.17	1.51	0.13
Proportion of 0–18 year olds in the population	−2.55	−2.77	0.006

could increase AE by using proportionally more dentists compared to other inputs (87.5% of the health centres should have used less dentists). In case of other personnel, the percentage was 81.5%, which means that most units could benefit from a slight increase in the number of other staff. There were less systematic misallocations concerning hygienists and materials; approximately half of the units underutilised and half overutilised these inputs. However, there were 70 PDS units employing exactly one hygienist, when the optimal, allocatively efficient use of hygienists would have been less than 1.0 full-time equivalent.

Determinants of efficiency

Variables reflecting need and demand, output structure, treatment practices and economic incentives and constraints of the municipality were found to be significant predictors of CE (Table 2). The explanatory power of the ordinary least squares method (Appendix: 3) revealed that some 30% of the variation in cost inefficiency could be explained by the variables used in this study.

A high state-subsidy predicted cost inefficiency ($P < 0.01$). CE was also found to be lower when the proportion of 0–18 year olds among the patients was high ($P < 0.001$) and when the number of dental visits per patient was high ($P < 0.001$). CE improved when the proportion of residents on disability pension was high ($P < 0.05$), when the cost of subsidised private dental care ($P < 0.05$) was high and when the municipality had young population ($P < 0.01$). The most important single determinant of CE was state subsidy. Our findings imply that a positive change in the state subsidy variable from its 1st quartile to its 3rd quartile would mean a 11.9% decrease in CE. A similar change in the number of visits per patient would result in an 11.3% decrease in CE.

Technical inefficiency was markedly and positively associated with a high proportion of young patients ($P < 0.01$), a high number of dental visits per patient ($P < 0.001$) and a high unemployment rate ($P < 0.05$), while a high proportion of residents on disability pension ($P < 0.01$), high cost of private dental care ($P < 0.05$) and young population in the municipality ($P < 0.05$) predicted efficiency (Table 3).

Allocative inefficiency resulted from high state subsidies ($P < 0.001$) and high level of education ($P < 0.05$) in the municipality. A high proportion of dentist to other employees ($P < 0.01$) and high proportion of dental hygienists to dentists ($P < 0.001$) were found to contribute to inefficiency. Again, the change in the value of state subsidy from its 25th percentile to its 75th percentile decreased AE by 9.4% (Table 4).

Discussion

The present study revealed wide differences in CE between municipal PDSs in Finland. The most important determinants of CE and AE were state subsidy levels, socioeconomic conditions of the municipality, treatment patterns and the emphasis on treatment of children and youngsters. The DEA model gave systematically lower CE and AE to PDS units with high state-subsidies. A high subsidy rate lowers the costs a municipality has to pay for inefficient use of resources. As there is a considerable informational asymmetry between PDS administration and municipal boards to which the health centre

Table 3. Tobit analysis using technical efficiency as the dependent variable

Predictor	Beta coefficient	*t*-ratio	*P*-value
Constant	1.17		
Proportion of municipal resident with higher education	−0.12 E-01	1.54	0.12
State subsidy per municipal resident	0.44 E-05	0.11	0.91
Tax revenue per resident (state + municipal)	−0.22 E-04	1.61	0.11
Proportion of municipal residents on disability pension	−0.41 E-02	−2.73	0.006
Proportion of unemployed in the municipality	0.12 E-01	2.24	0.03
Per capita expenditure on state-subsidised private dental care in the municipality	−0.23 E-02	−2.47	0.01
Proportion of dentists to other staff	−0.24	−1.65	0.10
Number of dental visits per person	0.18	7.33	0.000
Proportion of patients aged 0–18 years	0.14	3.49	0.001
DMFT mean in 6–18 year olds	−0.74 E-02	−0.24	0.81
Proportion of hygienists to dentists	−0.11	−1.07	0.28
Proportion of 0–18 year olds in the population	−1.82	−2.12	0.03

Table 4. Tobit analysis using allocative efficiency as the dependent variable

Predictor	Beta coefficient	*t*-ratio	*P*-value
Constant	−0.52		
Proportion of municipal residents with higher education	0.10 E-01	2.32	0.02
State subsidy per municipal resident	0.99 E-04	4.41	0.000
Tax revenue per resident (state + municipal)	−0.59 E-05	−0.75	0.46
Proportion of municipal residents on disability pension	−0.61 E-03	−0.72	0.47
Proportion of unemployed in the municipality	−0.47 E-02	−1.49	0.14
Per capita expenditure on state-subsidised private dental care in the municipality	−0.74 E-04	−0.14	0.89
Proportion of dentists to other staff	0.26	3.18	0.002
Number of dental visits per person	0.17 E-02	0.12	0.90
Proportion of patients aged 0–18 years	0.28 E-01	1.12	0.24
DMFT mean in 6–18 year olds	0.20 E-01	1.12	0.26
Proportion of hygienists to dentists	0.27	4.50	0.000
Proportion of 0–18 year olds	−0.95	−1.93	0.05

administrations are accountable, it is possible for the health centres to choose an inefficient level of performance. If resources are generous, the municipal board may have fewer incentives to monitor the cost efficiency of their health centre. Thus, also high income from municipal taxation and high level of resources per capita used for primary care may be positively correlated with inefficiency.

Previously, high state-subsidies have been associated with low CE in primary health care (16) and in dental care (9, 10). After the PDS was created in the early 1970s, municipalities were until 1993 encouraged to employ health care staff by offering remote and sparsely populated areas above average state subsidies; sometimes, the subsidies covered more than 60% of running costs. The staffing of the PDS has remained largely untouched in recent times, and it is likely that some units have excess resources compared with the treatment needs of the population. This situation invites closer co-operation and resource sharing between smaller municipalities.

A high proportion of under 19 year olds among the patients suggested inefficiency. Since the 1970s, the dental health of the younger populations has improved markedly in Finland. At present, most children and youngsters have good oral health (DMFT 12 years: 1.1 in 1997) and regional variations are small (unpublished data). Instead of annual examinations, extended recall intervals are recommended for healthy younger populations, which means breaking a long tradition in the PDS (17). In 1997, 81% of young people under 19 years old still visited the PDS and they made up 53% of patients. Similarly, 31% of the 19–41 year olds but only 13% of those over 41 years visited the PDS (12). Thus, the observed association could indicate that municipalities have failed to reallocate their resources because of the rapid improvement in dental health, especially among the younger age groups and especially in the municipalities with ageing populations.

A high number of visits per patient suggested inefficiency. The mean number of visits per patient varied between 1.4 and 4.0 among the different PDS units. It is possible that some PDS units boosted their output by splitting individual treatment episodes into several separate visits. However, it is possible that there were differences in the case-mix of the treatment measures, which may bias the estimates for CE and TE.

Other studies have found big differences between PDS units in numbers of preventive treatment measures provided, examinations and time devoted to orthodontic work in young patients (18, 19). These differences have been difficult to explain in terms of treatment needs and probably reflect local treatment traditions. The high numbers of visits in the young age groups are likely to be a consequence of too frequent examinations, preventive measures provided for both low- and high-risk individuals and long-duration orthodontic treatments commenced at ages younger than is customary in the other Nordic countries (19). As there is little evidence that all these treatments offer benefits (19, 20), much of them may be over-treatment and so unnecessary. The current remuneration system for public dentists in Finland, which adds a treatment-related 10–30% to basic salary, may encourage quick and easy treatments instead of slow and difficult ones. Also, economic analyses may give a PDS unit more credit for having a high number of easy patients rather than providing time-consuming difficult treatments for fewer adults in another unit. As no data were available to link an individual's treatment need with care provided and treatment outcome, rough estimates of outcome, such as numbers of patients and visits, had to be used.

The finding that substantial provision of private dental care in the municipality increased CE may reflect increasing treatment demands in middle-aged adults. The finding can also indicate that the private sector complements the PDS by taking care of the more resource-demanding adult patients (on average), which may in turn lead to a slight bias in our analysis: in areas where private care is plentiful, the PDS seems to select patients whose needs are less resource intensive.

The proportion of residents on disability pension is known to parallel morbidity and a higher demand for general health services. In our analyses, this factor increased efficiency, which could be explained using similar arguments as in the discussion about the effect of treatment patterns. It is easier for the municipalities to adjust resources to cost-efficient levels if there is sufficient demand for the services.

The variation in PDS units' decisions about input allocations was measured by the proportion of dentist full-time equivalents (FTEs) to other FTEs and the proportion of hygienists to dentists. According to the econometric model, CE could not be improved by shifting input allocation towards more auxiliary manpower, and a higher proportion of dentists did not seem to contribute to improved cost inefficiency. However, statistical testing of this relationship is often incapable of indicating problems in the input allocations. Some of the units may under-utilise dentist inputs and some over-utilise, and the total average effect cancels out in statistical analysis. However, DEA models are deterministic and non-parametric and allow for investigating the optimal allocations on an individual basis. In this study, it was found that a majority of the PDS units could increase AE by decreasing the relative number of dentist FTEs and increasing the use of auxiliaries. Interestingly, increasing the share of hygienists to dentists decreased efficiency. This was not in accordance with previous studies (21, 22). It must nevertheless be noted that most of the staffing optimal input levels obtained were non-integer figures. Optimal levels of staffing were rare because staff come in 'lumpy units'; it is difficult to employ personnel on a part-time basis. However, the supply of services is not merely a health policy issue, because employees generate income tax revenues for the municipalities that host the public dental clinics.

Although the material used was representative of public dental care in Finland and the quality of the data was satisfactory, there remained a number of limitations in the study. First of all, no valid measure for the case-mix could be used in the output measurement. In the present study, the number of treated patients was used as the unit of output. Second, aggregated data and the methods used may have caused bias in the efficiency estimates. The bias because of data aggregation and the DEA methodology both tend to overestimate efficiency. There was also some uncertainty about the correct interpretation of the variable measuring the average number of visits per patient.

The main findings of this study agree broadly with the results of previous studies in Finland. A recent British study using DEA also revealed similar results: many Community Dental Service units were under-performing (7). A Norwegian study (6) showed much better efficiency in the public dental care of children in Norway, because of cost containment and adjustment of staff to improvements in children's dental health. According to our findings, in Finland there is excess capacity, which could be used for extending the dental services to older age groups or to other purposes in many municipalities. This study suggests that many contributing factors and complex interactions determine efficiency in the PDS. Modern techniques for efficiency analysis combined with improved data on output measures and quality may become a useful tool in the strategic planning and management of the public dental services in the future.

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Appendix

Technical (TE) and scale (SCE) efficiency

The decomposition of cost efficiency into allocative and technical components was accomplished by first solving the following linear programme, which gives the input-oriented technical inefficiency component:

$$\begin{aligned}
&\mathrm{Min}_{z,\mu_i}\mu_i \\
\text{s.t.}\quad & z \cdot Y \geq y_i, \\
& z \cdot X \leq \mu \cdot x_i, \\
& z_i \geq 0 \\
& \sum_{i=1}^{n} z_i = 1
\end{aligned} \tag{1}$$

where Y is an $n \times m$ matrix of observed outputs for n units and X is an $n \times k$ matrix of inputs for each unit. The subscript i indicates the unit evaluated. z is an $1 \times n$ vector of intensity variables. The technical inefficiency component is given by the solution $\mathrm{TE} = \mu^*$. The input requirement set specifies a convex technology with variable returns to scale (VRS), which is imposed by the constraint $\sum_{i=1}^{n} z_i = 1$. Eliminating the summation, constraint changes the model to constant returns to scale (CRS). The scale efficiency measure SCE can be calculated as the ratio of CRS technical efficiency to VRS technical efficiency, $\mathrm{SCE} = \mathrm{TE}_{\mathrm{CRS}}/\mathrm{TE}_{\mathrm{VRS}}$.

Cost efficiency (CE)

The standard measure of cost efficiency is obtained via a two-stage process: (i) estimate the minimum price-adjusted resource usage given the technological constraints; and (ii) compare this minimum to the actual, observed costs (29). Formally, the cost minimisation model can be specified as:

$$\begin{aligned} &\mathrm{Min}_{z,x_i} \sum_j w_{ij} \cdot x_{ij} \\ &\text{s.t.} \quad z \cdot Y \geq y_i, \\ &\qquad z \cdot X \leq x_i, \\ &\qquad z_i \geq 0, \\ &\qquad \sum_i z_i = 1 \end{aligned} \tag{2}$$

where $w = (w_1, \cdots, w_k) \in R^k_+$ denotes input prices. The cost-minimising set of inputs x^* (a solution to model (2)) can then be used to estimate the cost efficiency (CE) by $\mathrm{CE} = w' \cdot x^* / w' \cdot x$, where x are actual, observed inputs used.

Allocative efficiency (AE)

Using models (1) and (2), the allocative efficiency can be calculated as $\mathrm{AE} = \mathrm{CE}/\mathrm{TE}$.