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Time and Quality Efficiency of Scotch Single Malt Whisky Production

An Empirical Two-Model DEA Approach

Magnus Richter

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List of abbreviations

b	Bottled
BCC	Banker/Charnes/Cooper
BM	Benchmark
CCR	Charnes/Cooper/Rhodes
CRS	Constant returns to scale
DEA	Data envelopment analysis
DMU	Decision making unit
H	High
L	Low
nm	New make
OE	Operational Efficiency
P	Productivity
ppm	Parts per million
Q	Quality
Q-DEA	Quality adjusted DEA
QE	Quality Efficiency
QE-DEA	Quality-driven, efficiency-adjusted DEA
s	Stored
TM DEA	Two-model DEA

List of variables and symbols

c_b	Alcoholic content (bottling)
c_nm	Alcoholic content (new make)
c_s	Alcoholic content (stored)
c_i	Cost per unit (input)
Δ	Difference
e_j	Revenue per unit (output)
i	Inputs ($i = 1, \ldots, m$)
j	Outputs ($j = m+1, \ldots, m+n$)
λ	Storage lots (time related)
Ω	DMU ($\Omega = 1, \ldots, O$)
ϕ_OE	Operational efficiency score
ϕ_QE	Quality efficiency score
s_a	Angels' share
t	Time
T	Planning horizon
y	Output quantity

1 Introduction

Due to the regulations of the Scotch Whisky Association, production of Scotch whisky requires a time input of at least 3 years of storage, otherwise the use of the term »whisky« is prohibited (Scotch Whisky Association 2009, p. 3). However, the majority of whiskies are nowadays stored for around 10–18 years, and some extraordinary sorts are even matured up to 70 years. Against the background of increasing storage and capital costs, it seems questionable that a distillery's management would choose long periods of storage time instead of bottling the final product as soon as possible. One possible explanation for this inventory policy might be the common opinion that older whisky is substantially better; an assertion which, in the paper at hand, will turn out to be false. In order to support rational managerial decision making in the Scotch whisky industry, it seems advisable to analyse the production of Scotch whisky and, particularly, the relevance of the input factor time, as well as its technological relationship to quality.

First of all, a general transformation function of Scotch whisky production is derived based on scientific literature on alcoholic beverage production technologies. The function discloses the main stages distilling, storing and bottling and formally links their input and output quantities to one another. It illustrates fundamental shifts between the quantities of new made distillate (stage 1 output), readily stored whisky (stage 2 output) and the final bottled product (stage 3 output). These shifts are generally controllable by the distilleries' management and, thus, serve as potential means for increasing efficiency. By providing a theoretical foundation of Scotch whisky technology, a set of key levers is revealed, which may be useful for further efficiency analysis and, thus, rational managerial decision making.

In order to evaluate the whiskies' quality efficiency and to identify sorts being produced with an efficient input of storage time – a further, more practical objective of this paper – a Two-Model-DEA (Sherman/Zhu 2006; Shimshak/Lenard 2007) is applied to empirical data taken from the Scottish whisky industry. The Two-Model DEA includes one operational efficiency and one quality efficiency model, which are calculated separately. Because the focus lies on quality-efficient whiskies (model 2), the distilleries' operational efficiency scores (model 1) were calculated within a preliminary study, which is outlined briefly. Whiskies originating from the distilleries remaining in the sub-set are benchmarked in terms of quality, which is measured using the four-dimensional rating scheme of the 2014 *Whisky Bible* (Murray 2014, p. 7). The quality-related model focusing on whisky sorts as DMUs reveals several important implications on how to allocate scarce resources, particularly time, more efficiently.

The paper contributes to operations management research in two ways: On the one hand, for the first time, a theoretical foundation for whisky production is provided by formalizing its essential transformation processes. Generalizing technologies of input/output relationships is crucial for efficiency analysis, particularly for the purposes of performance measurement using DEA. Furthermore, the terms of the whisky technology might be useful for economic analyses of other alcoholic beverage production processes, such as wine or cognac. On the other hand, the results may help to practically improve the distilleries' performances by revealing sources of quality-related inefficiencies, e. g. overly lengthy storage periods and the use of so called »age statements«, respectively.

The paper proceeds as follows: In section 2, the fundamentals of Scotch whisky production are described, including a definition of Scotch whisky and a literature review. In addition, the transformation function is modeled. In section 3, the properties of the basic DEA model and its quality-related extensions are depicted. Section 4 introduces the empirical data set and characterizes the model (inputs and outputs, distance measure, orientation and returns to scale). In addition, an artificial data set is developed that assumes a minimal storage time for each whisky sort. Due to the fact that a reduction of time input implies a (slight) decrease of output quality, the empirical quality scores for each whisky are adjusted and quality efficiency is re-calculated. A comparison between the original model and its artificial counterpart gives insights on how time contributes to quality, as well as which storage time is efficient. Section 5 concludes with a summary and concepts for further research objectives.

2 Basics of Scotch single malt production

2.1 Scientific research on whisky production

Whisky is defined as "a distilled spirit fermented from cereals, distilled at less than a maximum alcoholic strength (normally $<$ 94.8 per cent vol.) and matured in oak casks for a minimum period (typically three years). The normal minimum bottling strength for consumption is 40 per cent vol." (Aylott 2003, p. 276) To be labeled as »Scotch whisky« it must be "produced at a distillery in Scotland from water and malted barley" (Dolan 2003, p. 28). Further essential inputs are air (Dolan 2003, p. 28) and, occasionally, peat (Dolan 2003, p. 43). Aside from caramel, for the purpose of standardizing the colour, whisky may not content any other ingredients (Aylott 2003, p. 277). Scotch whisky production includes the main stages distilling, storing (or »aging«) and bottling, which open a wide range for managerial decision making and, thus, substantially affect efficiency.

Scientific research on whisky production seems very limited, particularly from the viewpoint of operations management. The vast majority of articles rather focuses on general research topics, such as classification schemes for whisky (Lapointe/Legendre 1994), or originates from engineering sciences. The latter analyse issues like materials and processing (Dolan 2003; Bringhurst/Broadhead/Brosnan

2003), yeast and fermentation (Campbell 2003), distillation (Campbell 2003; Nicol 2003) maturation (Conner/Reid/Jack 2003) and co-products (Pass/Lambert 2003). Economic publications hardly exist, apart from two articles on industrial change in the early Scotch whisky industry (Weir 1989; Bathgate 2003), a paper on forecasting and stock obsolescence (Grant/Karagianni/Li 2006) and a handbook chapter on marketing for whisky (Gordon 2003). The only scientific publication that directly affects the paper at hand is a working paper on industrial economics (Page 2013). PAGE raises the question of why distilleries produce multiple ages of whisky. He develops a theoretical model and shows, *inter alia*, that for a profit-maximizing distillery under perfect competition it can be rational to choose a product program including different ages, and that "most distilleries that produce multiple ages of whisky do not operate under perfect competition" (Page 2013, p. 1). Page's findings are related most closely to the so called »Angels' Share«, which is described in the following section.

2.2 A simple transformation function for scotch whisky production

Each distillation process (stage 1) produces an output quantity y_{nm} of so called *new make*, a distillate, which afterwards has to be stored (stage 2) in wooden casks. Storing *new make* causes a loss of approximately 2 % of the stored quantity p. a. (Page 2013, p. 5), a phenomenon which is called the *angels' share* ($s_{\text{a}} \approx 2$ %). The quantity of *new make* remaining in a cask (after the storage time t is over) is denoted by y_{s} (s := stored). This technological relationship shall be called the *angels' share transformation*, which is formalized by term (1):

$$y_{\text{s}} = y_{\text{nm}} \cdot \left(1 - s_{\text{a}}\right)^{t} \tag{1}$$

The final product being bottled (b) and sold to the customer usually has a lower alcoholic content (c) than *new make* (nm) ($c_{\text{b}} < c_{\text{nm}}$). Exceptions are the so called »cask strength whiskies« which are bottled (stage 3) without further dilution. If storage proceeds without complication, the ultimately stored (s) whisky maintains an alcoholic content of at least 40 % ($c_{\text{s}} \geq 40$ %). Although the alcoholic content of *new make* c_{nm} may vary during the storage process, depending on temperature (see e. g. Butzke/Vogt/Chacón-Rodríguez 2012 for analyses of temperature effects on wine), air pressure and further conditions of the warehouses (Conner/Reid/Jack 2003, p. 230), the analysis at hand is based on the assumption that it stays constant over time ($c_{\text{s}} = c_{\text{nm}}$). To lower the alcoholic content of the stored whisky (c_{s}), that is, the *new make* whose storage time has ended, to bottling strength (c_{b}), it is mixed with water. Thereby, the quantity of whisky being available for bottling (y_{b}) increases by the factor $c_{\text{s}}/c_{\text{b}}$. This technological issue shall be referred to as the *dilution transformation*, which is given by term (2):

$$y_{\text{b}} = y_{\text{s}} \cdot \frac{c_{\text{s}}}{c_{\text{b}}} \tag{2}$$

Due to the fact that some bottlings, as mentioned before, are sold in *cask strength*, the alcoholic content of bottled whisky (c_b) does not necessarily have to be lower than c_s, thus, $c_b \leq c_s$ applies as a further assumption.

Besides the transformation functions (1) and (2), an additional relationship has to be taken into account, which relates to the ratio of storage time t and the planning horizon T (both measured in years) that is chosen by the distillery's decision makers. According to this idea, each planning period, characterized by its length T, implies a number of time-related storage lots λ that depends on storage time t. Therefore, any given storage capacity is λ-times utilizable, with $\lambda = T/t$. This relationship, which shall be called the *time ratio transformation*, offers several valuable opportunities for decision makers with regard to sales planning, particularly the adaptation of output quantity in times of varying demand. The *time ratio transformation* affects the readily stored whisky quantity y_s – that is, at the same time, the quantity available for dilution – and, thus, (indirectly) the whisky quantity available for bottling and sales y_b in any given planning period, without affecting other input quantities required in earlier production stages.

Taken together, the three generic types of transformation (*angels' share transformation*, *dilution transformation* and *time ratio transformation*) shape the aggregate transformation function (3). The function (3) generally links the ultimate output quantity of Scotch whisky y_b to the quantity of *new make* y_{nm}, the *angels' share* s_a, the storage time t, the dilution factor c_s/c_b and the planning horizon T. This technological relationship is, by law, restricted by $t \geq 3$ years and $c_b \geq 40$ %.

$$y_b = y_{nm} \cdot (1 - s_a)^t \cdot \left(\frac{c_s}{c_b}\right) \cdot \left(\frac{T}{t}\right), \text{ with } t \geq 3,\ c_b \geq 40 \qquad (3)$$

Apart from the *angels' share*, which is supposed to be non-discretionary, all variables included in (3) are potential subjects of managerial decision making and, thus, may cause inefficiencies within the production process. Particularly the input time will be used for efficiency analysis in order to reveal opportunities to increase efficiency. Due to the fact that whisky quality is strongly affected by storage (stage 2), the analysis in chapter 4 – at least the quality efficiency model – focuses on storage and abstracts from distillation (stage 1) and bottling (stage 3). If, for instance, an analysis of the internal structures and component processes of whisky production was intended, a *Network DEA* (Färe 1991; Färe/Whittaker 1995) could be applied alternatively. "Separating large operations into detailed processes helps identify the real impact of input factors" (Kao 2014, p. 1) and, thus, may reveal sequential effects within the multi-stage production process.

3 Literature review and essentials of quality oriented DEA

3.1 Properties of the basic DEA-model

DEA (Charnes/Cooper/Rhodes 1978) is an instrument for measuring the relative efficiency of decision making units (DMUs) using multiple inputs and outputs. It has been extensively used (Seiford 1997), especially when the prices of inputs and outputs are unknown. Efficiency analysis would then be limited to the PARETO/KOOPMANS-criterion, which is based solely on comparisons of object quantities. Unfortunately, this criterion is limited to the binary distinction between efficient units and inefficient units. If, however, the performance of productive units has to be evaluated more precisely a weighting scheme is required, particularly when the sets of inputs ($i = 1, \ldots, m$) and outputs ($j = m+1, \ldots, m+n$) each contain two or more types of objects ($m, n \geq 2$) (Dyson et al. 2001, p. 248). This implies a changeover from pure quantitative models to efficiency concepts including distinct information on the decision maker's preferences (Dyckhoff/Allen 2001, p. 313). Usually, these preferences are expressed via market prices or weights, respectively. Therefore, DEA endogenously generates individual weights for each DMU Ω serving as substitutes for the missing market prices c_i (for the inputs i) and e_j (for the outputs j). This leads to a one-dimensional efficiency score ϕ^Ω for each DMU Ω. For this, the ratio of weighted output and weighted input of each DMU is maximized (see (4)) without exceeding an efficiency score of 1 when applying those weights to the inputs and outputs of each of the remaining O–1 DMUs under evaluation (see (5)) (Charnes/Cooper/Rhodes 1978, p. 430).

$$\max \phi^0 = \frac{\sum_{j=m+1}^{m+n} e_j \cdot y_j^0}{\sum_{i=1}^{m} c_i \cdot x_i^0} \tag{4}$$

so that

$$\frac{\sum_{j=m+1}^{m+n} e_j \cdot y_j^\Omega}{\sum_{i=1}^{m} c_i \cdot x_i^\Omega} \leq 1 \qquad \Omega = 1, \ldots, O \tag{5}$$

$$c_i, e_j \geq 0 \tag{6}$$

A DMU Ω is declared as efficient if its efficiency score ϕ^Ω is 1 or inefficient if < 1. If the analysis is restricted to goods (desirable objects), the prices c_i and e_j are positive (see (6)).

3.2 Quality aspects in DEA

Originally invented for the purpose of operational efficiency analysis, DEA is by now also used for qualitative benchmarking (Bowen 1990; Chilingerian/Sherman 1990). Several approaches have been proposed for incorporating quality into DEA, which differ in terms of suitability and quantitative results (Sherman/Zhu 2006). The first approach implies a quantification of qualitative data in order to add it to the common output set (see table 4 in the appendix for a survey). Although this approach, according to certain researchers (e. g. Cook 2004, p. 153), seems appropriate for modeling specific outputs, others questioned the mix between quality and quantity that was consequently implied (Chilingerian/Sherman 1990; Sherman/Zhu 2006; Shimshak/Lenard 2007). Quality/quantity trade-offs were said to mix both categories inadmissibly, so that technical efficiency could be attained by shortfalls in quality *et vice versa* (Sherman/Zhu 2006, p. 307; Chang/Yang 2010, p. 83). To avoid such deficiencies, operational and qualitative efficiency should be modeled and evaluated separately. The following DEA approaches of modeling the two types of efficiency separately can be found in the DEA literature:

- *Quality adjusted DEA* (Q-DEA) (Sherman/Zhu 2006)
- *Two-model DEA* (TM DEA) (Shimshak/Lenard 2007; for some preliminary contributions see Soteriou/Stavrinides 1997; Soteriou/Zenios 1999; Kamakura/Mittal/De Rosa 2002)
- *Quality-driven, efficiency-adjusted DEA* (QE-DEA) (Zervopoulos/Palaskas 2011).

Q-DEA models analyse the performance of DMUs in terms of operational efficiency as well as quality efficiency, both of which can be declared either as high (H) or low (L). According to this system, each DMU can be assigned to one of the four categories (HQ-HP, HQ-LP, LQ-HP, LQ-LP) depicted in figure 1.

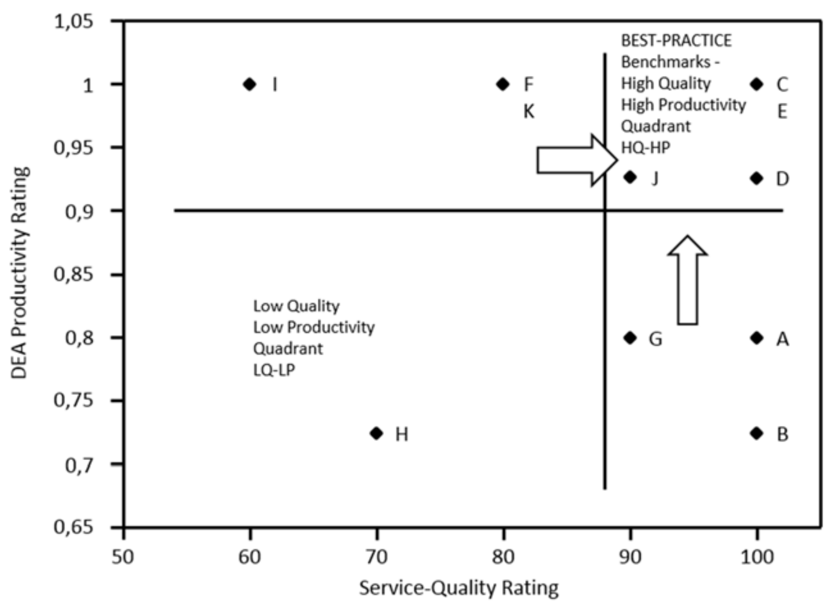

Figure 1. Independent quality and productivity dimensions in DEA (Sherman/Zhu 2006, p. 308)

Afterwards, DMUs that do not reach certain minima, being defined by the decision maker, are eliminated. For the remaining DMUs, the efficiency scores are re-calculated until there is no underperforming DMU left. This methodology ensures that, e. g., no DMU producing at a quality level deemed too low is used as an operational efficiency benchmark. The Q-DEA approach was invented to allow for more than a single measure of output quality (Shimshak/Lenard 2007, p. 149; Chang/Yang 2010, p. 84).

Like Q-DEA, TM DEA avoids 'dumping' quality as misconstrued pseudo-quantities within the output set (Shimshak/Lenard 2007, p. 149). Further similarities between TM DEA and Q-DEA are the option of using multi-dimensional quality measures (see Solà/Prior 2001, p. 229, for a health care example), minimum levels both for the operational and the quality efficiency, the elimination of DMUs who fail as well as the iterative re-calculation of efficiency scores. A major difference to Q-DEA is that TM DEA *reciprocally* eliminates all DMUs that have low operational efficiency scores from the quality efficiency model *et vice versa*. Taken together, the TM DEA approach seems most appropriate for the purposes of the paper at hand; therefore, the model presented in section 4 is based on the TM DEA methodology.

In contrast to Q-DEA and TM DEA, QE-DEA models (Zervopoulos/Palaskas 2011), do not eliminate underperforming DMUs from the reference set but replace them with hypothetical counterparts (Zervopoulos/Palaskas 2011, p. 406). The purpose of QE-DEA is "to determine the quality–efficiency benchmarks and the optimum combination of inputs and outputs for the non-effective operational units to meet the HQ-HE criteria." (Zervopoulos/Palaskas 2011, p. 414)

4 Two-model DEA of Scotch whisky production

4.1 Empirical data and model specification

The analysis uses as DMUs Scotch single malt whiskies listed in the 2014 *Whisky Bible* that contain distinct age statements and are bottled at a distillery still operating as well as the corresponding distilleries. 35 distilleries and 212 whiskies were included in the original data set. To focus only on distilleries processing at a high level of operational efficiency, an initial model (model 1) with distilleries as DMUs was calculated using a non-oriented envelop approach with constant returns to scale (CRS). Distillery-related inputs for this model are the quantities of mash tuns, washbacks, stills and capacity (Gänsmantel 2015) as well as the number employees (Jackson 2010; Maclean 2010; Hoffmann 2012). The produced whisky quantity per year was used as an output (Hoffmann 2012). All efficiency scores were calculated using *MaxDEABasic*. The input/output sets of both models are shown in figure 2.

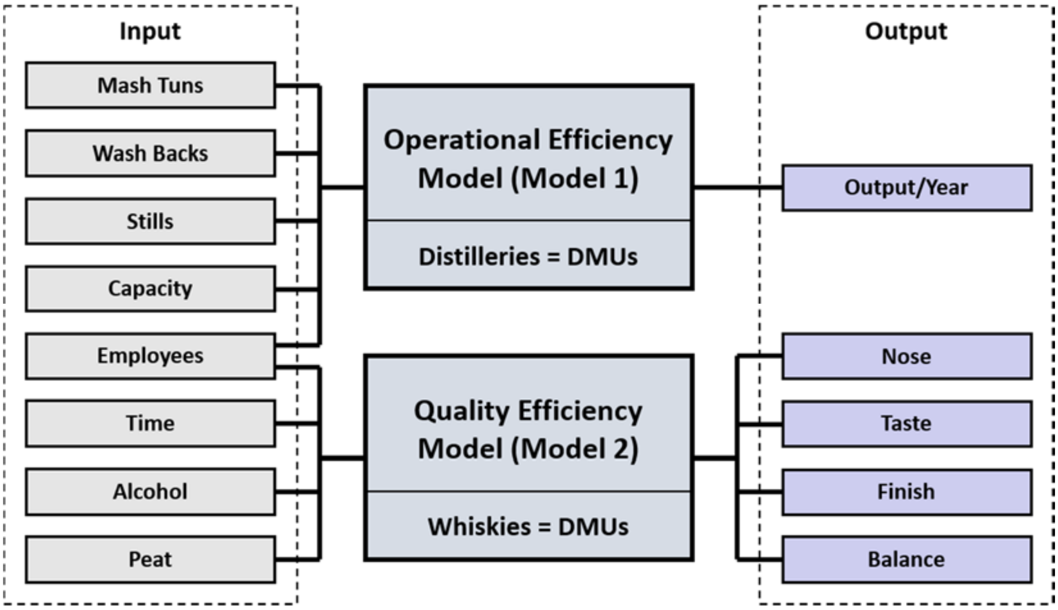

Figure 2. Input/output sets of the two DEA models

Distilleries that did not reach an operational efficiency score of presumed $\phi_{OE} \geq 0.70$ (model 1) were eliminated from all further analysis. 23 distilleries remained in the sub-set, producing 83 whisky sorts (analysed in model 2). Furthermore, a minimum for the quality efficiency scores of $\phi_{QE} \geq 0.80$ was defined (for model 2), which had to be reached by at least one of every distilleries' whisky sort. Due to the fact that *no* whisky sort being produced by the distillery of CLYNELISH reached the quality efficiency minimum $\phi_{QE} \geq 0.80$ (in the quality efficiency model which was calculated afterwards) CLYNELISH was *ex post* eliminated from the distillery set, and the operational efficiency scores ϕ_{OE} for the remaining 22 distilleries were re-calculated. The final results are shown in table 1.

DMU/Distillery	Operational Efficiency ϕ_{OE}	DMU/Distillery	Operational Efficiency ϕ_{OE}
Aberfeldy	0.7143	Laphroaig	0.7407
Ardbeg	0.7308	Macduff	0.8000
Caol Ila	1.0000	Oban	1.0000
Dalmore	0.8562	Royal Brackla	0.8667
Deanston	1.0000	Royal Lochnagar	0.8000
Fettercairn	0.7500	Scapa	1.0000
Glen Elgin	0.7200	Speyburn	0.7500
Glen Moray	0.7400	Strathisla	1.0000
Glenkinchie	1.0000	Tamdhu	1.0000
Glenmorangie	0.9756	Tomatin	1.0000
Lagavulin	0.9200	Tomintoul	1.0000

Table 1. Distilleries' operational efficiency scores

Afterwards, the quality efficiency model (model 2) with whisky sorts as DMUs was run applying an input-oriented CRS approach in envelop form and a radial distance measure (Farrell 1957). As depicted in figure 2 time, alcohol, peat and the number of employees served as inputs. Outputs incorporated into the quality model emerged from the rating categories *nose*, *taste*, *finish* and *balance* found in the *Whisky Bible* (Murray 2014, p. 7), each ranging from 0 (worst) to 25 points (best).

Peat contents were gathered online, and whiskies being declared as »unpeated« were rated with 0 parts per million (ppm). Categorical data concerning the peat content was quantified approximately in the middle of the intervals, referring to the proposals of Withers et al. (1996, p. 354): »peated« (< 5ppm): 3ppm; »medium« (3–15ppm): 10ppm; »heavily« (15–50ppm): 30ppm.

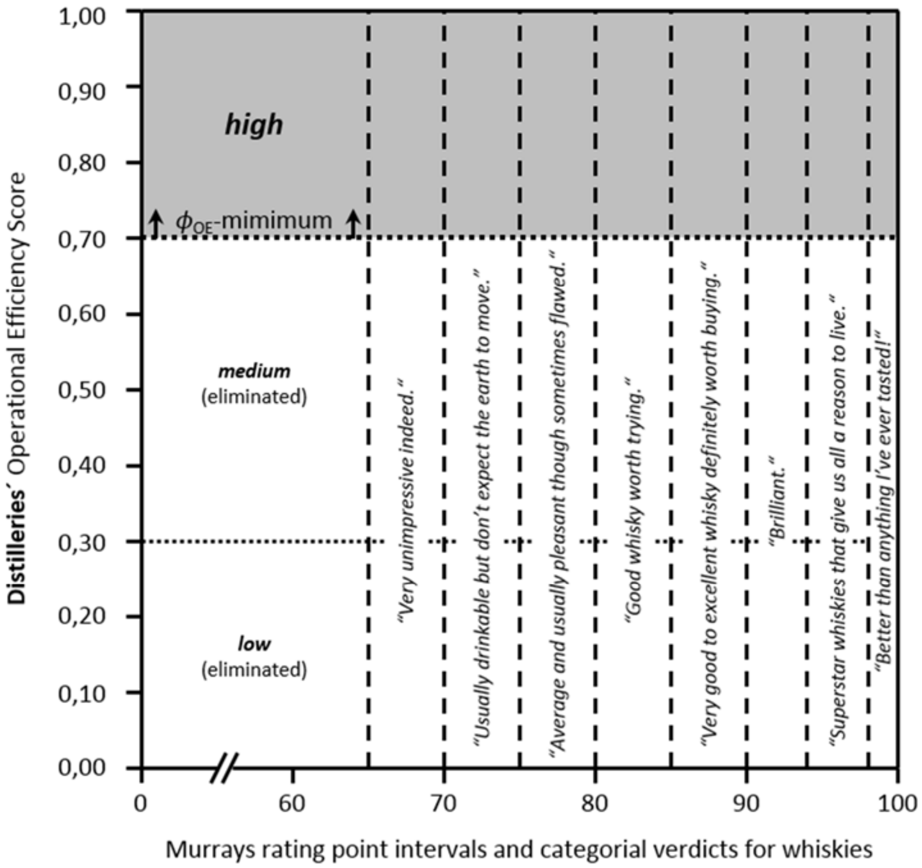

Figure 3. Distilleries' operational efficiency score and MURRAYS output quality points

With 82 whiskies originating from the distilleries listed in table 1, the number of DMUs in the quality efficiency model is sufficiently high compared to the number of input and output classes included in the input/output set (Dyson et al. 2001, p. 248): $82 > 32 = 2 \cdot i \cdot j$. The grey top area in figure 3 represents the set of 82 whisky sorts serving as DMUs within the quality efficiency model (stemming from the 22 operationally highly efficient distilleries listed in table 1). Each whisky sort under quality efficiency evaluation has been rated by MURRAY and, thus, exhibits a specific number of points scored in the four tasting categories (i. e. LAPHROAIG *10 Years Old*: 90 points; nose: 24 points, taste: 23 points, finish: 20.5 points and balance: 22.5 points (Murray 2014, p. 165). The columns in figure 3 (from 65 up to 100 points) refer to the sum of points given to the whisky sorts and, thus, are the basis for calculating their quality efficiency scores.

Since the inputs of the quality DEA model (see again figure 2) are more at the discretion of the distilleries' management than the specific rating scores (which significantly depend on one's expertise and sensual perception) an input-oriented model was chosen. Tests for scale effects based on graphical comparisons between BCC and CCR scores (see Dyckhoff et al. 2008, p. 64) furthermore suggest a CRS model (constant returns to scale). The whiskies' quality efficiency scores are shown in table 2. Qualitatively efficient whiskies are highlighted in bold, and in addition, information is given on how often efficient whiskies served as benchmarks (see "# BM" in the first row of table 2). Approximately 21 % (17 of 82) of the whiskies under evaluation are efficient, the average efficiency score amounts 0.89 and the range of efficiency scores is about 0.33; this indicates a reliable model specification.

The 'quality efficiency loser' e. g. is GLENKINCHIE *20* which was bottled after 20 years of storage with 58.4 % alcoholic content and no peat. It was rated with 85.5 points (nose: 21 points, taste: 22 points, finish: 21.5 points, balance: 21 points) and achieved a quality efficiency score of $\phi_{QE} \approx 0.67$.

With respect to the aggregate transformation function (3) (see again section 2.2) it seems advisable to look for means of increasing quality efficiency, all the more so since 16 whiskies achieved quality efficiency scores $\phi_{QE} < 0.80$. As shown in term (3), several influencing factors on quality efficiency exist. These can be varied in order to increase efficiency, particularly the input storage time.

According to that, the widely held belief that older whiskies *ceteris paribus* are better than younger whiskies should be questioned, unless a significant part of the qualitatively inefficient whiskies listed in table 2 (as well as some of the whiskies rated as poor in terms of MURRAY-points) have been stored for long periods of time, such as GLENKINCHIE *20*, TOMATIN *21*, and FETTERCAIRN *30*.

Statistical analysis of the empirical data gathered indicates a correlation greater than 0.2 only for the relationship between age (storage time) and nose. Overall, correlation between age and the sum of MURRAY-points given to the whiskies analysed amounts ≈ 0.15. The results suppose that a firm's objective of producing high quality whisky is not substantially supported by longer storage times. To increase its rating score by, e. g., 3 MURRAY-points, a whisky would have to be stored for another 20 years. The popular assessment '*The older, the better*', thus, does not convincingly hold – at least for the data being published in the 2014 *Whisky Bible*. Distilleries' rational decision-making, therefore, implies considerably shorter periods of storage, in extreme cases as far as to the legal minimum (3 years).

No.	DMU/Whisky sort	ϕ_{QE}	# BM	No.	DMU/Whisky sort	ϕ_{QE}	# BM
1	Aberfeldy 12	0.9565	0	42	Lagavulin 21 SR 2012	0.7959	0
2	**Ardbeg 10**	**1.0000**	5	43	**Laphroaig 10**	**1.0000**	11
3	Ardbeg 10 L10 152	0.9952	0	44	Laphroaig 10 CS Batch 001	0.7578	0
4	**Ardbeg 17 Early**	**1.0000**	10	45	Laphroaig 10 Original CS	0.7983	0
5	**Ardbeg 17 Later**	**1.0000**	0	46	Laphroaig 15	0.8004	0
6	Caol Ila 10U	0.9273	0	47	Laphroaig 18	0.8396	0
7	Caol Ila 12	0.9632	0	48	Laphroaig 25 CS 2011 Edition	0.8491	0
8	Caol Ila 12 SR10	0.8882	0	49	**Laphroaig 25 Sherry**	**1.0000**	5
9	Caol Ila 12 SR11	0.8183	0	50	Laphroaig 30	0.9401	0
10	Caol Ila 14	0.7978	0	51	Laphroaig 40	0.9460	0
11	Caol Ila 18	0.8351	0	52	**Macduff 10**	**1.0000**	34
12	**Caol Ila 8 1st**	**1.0000**	0	53	Macduff 15	0.9806	0
13	**Caol Ila 8U**	**1.0000**	6	54	Oban 14	0.8793	0
14	**Dalmore 12**	**1.0000**	16	55	Oban 15 DE Bottled 1992	0.9236	0
15	Dalmore 12 Dee	0.7350	0	56	Oban 15 DE Bottled 1993	0.9600	0
16	Dalmore 15	0.9064	0	57	Royal Brackla 10	0.8871	0
17	Deanston 12	0.7445	0	58	Royal Lochnagar 12	0.9787	0
18	Deanston 12 Aged	0.8140	0	59	**Scapa 12**	**1.0000**	34
19	**Deanston 6**	**1.0000**	27	60	**Scapa 14**	**1.0000**	17
20	Fettercairn 12	0.8196	0	61	Scapa 16	0.9254	0
21	Fettercairn 30	0.6794	0	62	**Scapa 16 Orcadian**	**1.0000**	0
22	**Fettercairn 40**	**1.0000**	0	63	Speyburn 10	0.9464	0
23	Glen Elgin 12	0.9924	0	64	Speyburn 25	0.9064	0
24	Glen Moray 10	0.8573	0	65	Strathisla 12	0.9867	0
25	**Glen Moray 8**	**1.0000**	7	66	Strathisla 15	0.8432	0
26	Glenkinchie 12	0.9392	0	67	Tamdhu 10	0.8174	0
27	Glenkinchie 15	0.9228	0	68	Tamdhu 18	0.7498	0
28	Glenkinchie 20	0.6710	0	69	Tamdhu 25	0.9125	0
29	Glenmorangie 12 Lasanta	0.7174	0	70	Tomatin 12 1997	0.7769	0
30	Glenmorangie 12 Nectar D'Or	0.9580	0	71	Tomatin 12 Years Old	0.9649	0
31	Glenmorangie 18	0.9430	0	72	Tomatin 15 Aged 15 Years	0.8784	0
32	Glenmorangie 25	0.9692	0	73	Tomatin 15 Years Old	0.7759	0
33	Lagavulin 12 10th	0.7949	0	74	Tomatin 18 Aged 18 Years	0.9117	0
34	Lagavulin 12 7th	0.7838	0	75	Tomatin 18 Aged 18 Sherry	0.8718	0
35	Lagavulin 12 8th	0.8089	0	76	Tomatin 18 Aged 18 Years Old	0.8704	0
36	Lagavulin 12 SR 2010	0.8156	0	77	Tomatin 21	0.7353	0
37	Lagavulin 12 SR 2011	0.8185	0	78	Tomintoul 12 Oloroso	0.8321	0
38	Lagavulin 12 SR 2012	0.8071	0	79	Tomintoul 12 Port	0.8806	0
39	Lagavulin 16	0.9776	0	80	**Tomintoul 16**	**1.0000**	33
40	Lagavulin 16 DE PX Cask	0.8628	0	81	**Tomintoul 21**	**1.0000**	12
41	Lagavulin 21	0.7573	0	82	Tomintoul 27	0.9462	0

Table 2. Whiskies' quality efficiency scores

4.2 Comparison with an artificial 3-years-storage model

In order to analyse the hypothesis that age does not contribute substantially to whisky quality and, in other words, that quality efficiency can be increased by reducing storage time, the original data set is subsequently analysed in even more detail. Therefore, the original data set is compared to an artificial counterpart, which is generated as follows: First of all, the assumption is set that each whisky, instead of its original age, has been stored for only 3 years.

Based on the correlation factors calculated for the relationships between age and the output quality criteria nose ($\approx$ 0.20), taste ($\approx$ 0.10), finish ($\approx$ 0.11) and balance ($\approx$ 0.17), the rating points achieved in these categories were adjusted. An 18 year old whisky's nose-rating of, e. g., 93 points would be updated to 90, according to the fact that its fictional counterpart is 15 years younger, and in each of these years statistically 0.20 nose-points would have been generated. According to this idea, the calculation reads as follows: $93 - ((18–3) \cdot 0.20) = 90$. This was done for each whisky regarding each of their output rating scores. Afterwards, efficiency scores were re-calculated, based on the assumption that all other quantities remained unchanged.

Table 3 shows the re-calculated quality efficiency scores based on the adjusted scores of the four output criteria (as well as the former quality efficiency scores). The percentage efficiency changes are listed in the columns Δ [%]. Thereby, 17 whiskies have become efficient (marked in bold), whereas 6 sorts lost their status as efficient benchmarks (marked in italics). Quality efficiency increases by an average of $\approx$ 7.1 %. With respect to managerial decision making, it is noteworthy that the largest increase of quality efficiency is achievable by middle-aged whiskies (see figure 4). Between an interval of 10–20 years there is a strong potential increase in quality efficiency. Only very old whiskies ($t \geq 37$) do not leave any opportunity for improving quality efficiency by rejuvenation.

Hence, a reduction of storage time seems highly recommended, particularly for middle-aged whiskies, for which demand, incidentally, is very strong nowadays. So the biggest efficiency improvements particularly affect whisky sorts being produced in very large quantities. The relevance of this insight for managerial decision making lies at hand, all the more because reducing storage time not only increases quality efficiency but *ceteris paribus* also operational efficiency: The total quantity of whisky, as shown in (3), depends on the ratio T/t as well as on the *angels' share*, both which can be optimized by reducing t. Doing so can consequently be regarded as '*killing two birds with one stone*'.

Increasing quality and operational efficiency by reducing storage time, however, presupposes that the customers' purchasing decision is not significantly affected by age statements, that is to say the misconception of '*The older, the better*'.

No.	DMU	ϕ_{QE}	Adjusted	Δ [%]	No.	DMU	ϕ_{QE}	Adjusted	Δ [%]
1	Aberfeldy 12	0.9565	0.9370	-2.037	42	Lagavulin 21 SR 2012	0.7959	0.9629	20.981
2	Ardbeg 10	1.0000	1.0000	0.000	43	Laphroaig 10	1.0000	1.0000	0.000
3	**Ardbeg 10 L10 152**	**0.9952**	**1.0000**	**0.482**	44	Laphroaig 10 CS Batch …	0.7578	0.9754	28.712
4	Ardbeg 17 Early	1.0000	1.0000	0.000	45	Laphroaig 10 Original CS	0.7983	0.9916	24.213
5	Ardbeg 17 Later	1.0000	1.0000	0.000	46	Laphroaig 15	0.8004	0.8317	3.915
6	**Caol Ila 10U**	**0.9273**	**1.0000**	**7.842**	47	Laphroaig 18	0.8396	0.9693	15.446
7	Caol Ila 12	0.9632	0.9853	2.296	48	**Laphroaig 25 CS 2011 …**	**0.8491**	**1.0000**	**17.772**
8	**Caol Ila 12 SR10**	**0.8882**	**1.0000**	**12.591**	49	Laphroaig 25 Sherry	1.0000	1.0000	0.000
9	Caol Ila 12 SR11	0.8183	0.9832	20.144	50	Laphroaig 30	0.9401	0.9488	0.932
10	**Caol Ila 14**	**0.7978**	**1.0000**	**25.346**	51	Laphroaig 40	0.9460	0.9858	4.206
11	Caol Ila 18	0.8351	0.9779	17.100	52	Macduff 10	1.0000	1.0000	0.000
12	Caol Ila 8 1st	1.0000	1.0000	0.000	53	Macduff 15	0.9806	0.9757	-0.502
13	*Caol Ila 8U*	*1.0000*	*0.8469*	*-15.307*	54	Oban 14	0.8793	0.9150	4.065
14	*Dalmore 12*	*1.0000*	*0.9996*	*-0.039*	55	Oban 15 DE Bottled 1992	0.9236	0.9692	4.932
15	Dalmore 12 Dee	0.7350	0.7174	-2.386	56	**Oban 15 DE Bottled …**	**0.9600**	**1.0000**	**4.170**
16	Dalmore 15	0.9064	0.8999	-0.717	57	Royal Brackla 10	0.8871	0.8609	-2.954
17	**Deanston 12**	**0.7445**	**1.0000**	**34.311**	58	Royal Lochnagar 12	0.9787	0.9676	-1.140
18	Deanston 12 Aged	0.8140	0.7975	-2.027	59	Scapa 12	1.0000	1.0000	0.000
19	*Deanston 6*	*1.0000*	*0.8952*	*-10.475*	60	Scapa 14	1.0000	1.0000	0.000
20	Fettercairn 12	0.8196	0.7938	-3.155	61	Scapa 16	0.9254	0.9140	-1.225
21	Fettercairn 30	0.6794	0.7409	9.042	62	*Scapa 16 Orcadian*	*1.0000*	*0.9891*	*-1.091*
22	*Fettercairn 40*	*1.0000*	*0.9925*	*-0.754*	63	Speyburn 10	0.9464	0.9348	-1.231
23	**Glen Elgin 12**	**0.9924**	**1.0000**	**0.767**	64	Speyburn 25	0.9064	0.9952	9.793
24	**Glen Moray 10**	**0.8573**	**1.0000**	**16.647**	65	**Strathisla 12**	**0.9867**	**1.0000**	**1.348**
25	*Glen Moray 8*	*1.0000*	*0.8068*	*-19.321*	66	**Strathisla 15**	**0.8432**	**1.0000**	**18.596**
26	Glenkinchie 12	0.9392	0.9676	3.018	67	Tamdhu 10	0.8174	0.7783	-4.781
27	**Glenkinchie 15**	**0.9228**	**1.0000**	**8.367**	68	Tamdhu 18	0.7498	0.7889	5.212
28	Glenkinchie 20	0.6710	0.9122	35.952	69	Tamdhu 25	0.9125	0.9118	-0.078
29	Glenmorangie 12 Lasanta	0.7174	0.7908	10.219	70	Tomatin 12 1997	0.7769	0.9610	23.697
30	**Glenmorangie 12 Nectar …**	**0.9580**	**1.0000**	**4.382**	71	Tomatin 12 Years Old	0.9649	0.9980	3.428
31	Glenmorangie 18	0.9430	0.9716	3.042	72	Tomatin 15 Aged 15 Years	0.8784	0.9258	5.396
32	Glenmorangie 25	0.9692	0.9969	2.856	73	Tomatin 15 Years Old	0.7759	0.9564	23.268
33	Lagavulin 12 10th	0.7949	0.9565	20.332	74	Tomatin 18 Aged 18 Years	0.9117	0.8940	-1.945
34	**Lagavulin 12 7th**	**0.7838**	**1.0000**	**27.585**	75	Tomatin 18 Aged 18 …	0.8718	0.9197	5.496
35	Lagavulin 12 8th	0.8089	0.9937	22.838	76	Tomatin 18 Aged 18 …	0.8704	0.9757	12.106
36	**Lagavulin 12 SR 2010**	**0.8156**	**1.0000**	**22.610**	77	Tomatin 21	0.7353	0.9331	26.908
37	Lagavulin 12 SR 2011	0.8185	0.9986	22.001	78	Tomintoul 12 Oloroso	0.8321	0.8033	-3.461
38	**Lagavulin 12 SR 2012**	**0.8071**	**1.0000**	**23.894**	79	Tomintoul 12 Port	0.8806	0.9363	6.321
39	**Lagavulin 16**	**0.9776**	**1.0000**	**2.293**	80	Tomintoul 16	1.0000	1.0000	0.000
40	Lagavulin 16 DE PX Cask	0.8628	0.8855	2.630	81	Tomintoul 21	1.0000	1.0000	0.000
41	Lagavulin 21	0.7573	0.9763	28.924	82	Tomintoul 27	0.9462	0.9347	-1.222

Table 3. Comparison between former and adjusted quality efficiency scores

If, however, the customers' perceived whisky quality depends on this conviction, selling younger whiskies *successfully* might not be that easy. Traditionally, the vast majority of customers *is* affected by age statements and assumes this denotes high quality – mainly when declared ages are high. Thus, the declaration of short storage times may cause a decline in the distilleries' overall revenues, all the more so since older whiskies tend to achieve disproportionately high(er) prices per unit.

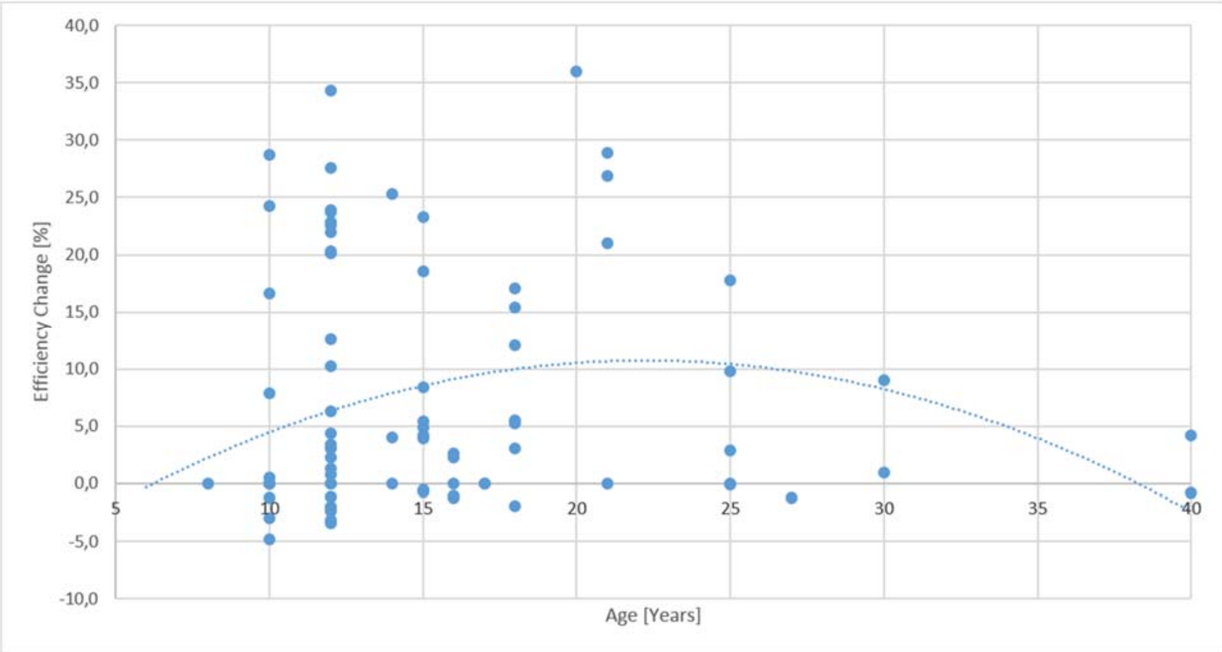

Figure 4. Interplay between whisky age and quality efficiency change

A more sophisticated method of reducing storage time without deterring customers is the use of so called »non-age statements« (*nas*), which are characterized by a total abandonment of explicit age declarations. Exceedingly successful examples of *nas* are given by the distillery of ARDBEG which names its whiskies exclusively after special places, events or techniques such as, e. g., »Kildalton«, »Galileo« or »Alligator«. ARDBEG avoids excessive storing times by drawing the customer's attention to entertaining background information concerning a whisky's provenience or genesis. Nonetheless, it remains to be examined to what extent *nas* may serve as suitable replacements for the (obviously) irrational but well-established pseudo-quality indicator age.

5 Summary

The main objective of this study was to illustrate the relevance of time for Scotch whisky production and its technological relationship to quality. Using a two-stage DEA model, 22 distilleries reaching an operational efficiency level $\phi_{OE} \geq 0.70$ were identified (model 1), and their whiskies' quality efficiency was subsequently benchmarked in more detail (model 2). Output quality was measured using the categories nose, taste, finish and balance of MURRAYS so called *Whisky Bible*. Employees, storage time, alcohol content and peat served as inputs.

To impart a deeper understanding of the whisky technology underlying the production process, an aggregate transformation function was developed. It consists of three generic transformations called *angels' share transformation*, *dilution transformation* and *time ratio transformation*, each of which referring to one of the main stages of Scotch whisky production. This function indicates that the quantity of whisky ultimately available for bottling and sales, respectively, not only depends on the quantity of *new make* originally distilled, but also on the *angels' share*, the alcoholic content of *new make* and the final bottled product, as well as the planning horizon and, most important in this case, storage time.

The empirical results indicate only a minor contribution of storage time to whisky quality and, thus, by trend decreasing quality efficiency scores for older whiskies. To gain deeper insights into quality efficiency issues related to time, a hypothetical data set was construed based upon the original data set: Each whisky's original age was reduced to fictional 3 years and its quality points were adjusted according to the corresponding correlation factors (age–nose, age–taste, age–finish and age–balance). Quality efficiency scores were re-calculated for this supplementary artificial data set and compared to the initial results. It turned out that the largest increases of quality efficiency are achieved by middle-aged whiskies of approximately 10–20 years. The average increase of quality efficiency amounts ≈ 7.1 %.

Rejuvenation not only increases whiskies' quality efficiency but, at the same, distilleries' operational efficiency as a result of the *time ratio transformation* and the *angels' share transformation*: Firstly, the quantity of whisky evaporating during storage is reduced, and, secondly, a distillery's capacity can be utilized more often. Producing younger whiskies, therefore, seems like '*Killing two birds with one stone*'. However, a limitation may be the customers' widespread conviction that older whiskies are significantly better – an assumption that turned out to be false. Therefore, a distillery's manager should keep in mind that using age statements for younger whiskies may deter potential customers. A more sophisticated way to save time might be the use of non-age statements. One thing still yet to be analysed, hence, is the suitability of non-age statements as substitutes for the questionable but well-established quality indicator age – particularly since older single malt whiskies tend to achieve disproportionately high(er) prices per unit.

Appendix

Year	Author(s)	Subject	Output Quality Measures
1984	Bessent *et al.*	Public schools	Average test scores
1986	Thompson *et al.*	Site selection	Facility costs, user costs, environmental impact
1990	Bowen	Site selection	1–10 scale for depot accessibility and amenities
1991	Callen	Hospitals	Number of patient days for different age classes
1994	Doyle and Green	Micro computers	Memory/disk size, CPU speed, disk access speed
1995	Morey *et al.*	Hospital health care	Ratio of actual and forecasted numbers of deaths
1995	Olesen and Petersen	Primary schools	Amount of pupils at or above a specific test score
1995	Thanassoulis *et al.*	Perinatal care	Number of (very) satisfied mothers
1996	Cook *et al.*	R&D projects	Savings created by energy efficient devices [$]
1996	Salinas-Jiménez/Smith	Primary health care	Practices employing a nurse [%]
1997	Athanassopoulos	Financial services	Number of deposit accounts, credits, debits
1997	Chlingerian/Sherman	Primary health care	Number of patients in age/gender categories
1997	Rouse *et al.*	R&D projects	5-Point Likert-scale for management satisfaction
1998	Ray/Mukherjee	Public schools	Students pursuing further education [%]
2001	Adler/Berechman	Airports	Number of restaurants, processing time
2001	Solà/Prior	Catalan hospitals	In-patient days spent, visits, infections
2002	Forker/Mendez	Peer suppliers	Defective parts delivered [parts per million]
2002	Rouse *et al.*	Aircraft maintenance	Positive and negative points for service quality
2003	Wagner *et al.*	Physician profiling	Inpatients not readmitted/without complications [%]
2005	Blose *et al.*	Grocery stores	Net profit, customers/labor hours, customer loyalty
2010	Oh *et al.*	Automobile market	Volume, fuel efficiency, maximum horsepower
2010	Shimshak	Nursing homes	Number of residents with catheter
2011	Garavaglia *et al.*	Nursing homes	Extra nursing hours, patient satisfaction
2013	Ferrier/Trivitt	Hospitals	Mortality rate within 180 days of discharge
2013	Tavakoli *et al.* (a; b)	Private banks	Items from SERVQUAL
2014	Lee/Kim	Auto repair services	Items from SERVPERF

Table 4. Publications modeling quality as quantitative output

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