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Published Version

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To link to this article DOI: http://dx.doi.org/10.1080/01446193.2015.1059951

Publisher: Taylor & Francis

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Scoring rules and abnormally low bids criteria in construction tenders: a taxonomic review

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Received 20 October 2014; accepted 4 June 2015

In the global construction context, the best value or most economically advantageous tender is becoming a widespread approach for contractor selection, as an alternative to other traditional awarding criteria such as the lowest price. In these multi-attribute tenders, the owner or auctioneer solicits proposals containing both a price bid and additional technical features. Once the proposals are received, each bidder’s price bid is given an economic score according to a scoring rule, generally called an economic scoring formula (ESF) and a technical score according to pre-specified criteria. Eventually, the contract is awarded to the bidder with the highest weighted overall score (economic + technical). However, economic scoring formula selection by auctioneers is invariably and paradoxically a highly intuitive process in practice, involving few theoretical or empirical considerations, despite having been considered traditionally and mistakenly as objective, due to its mathematical nature. This paper provides a taxonomic classification of a wide variety of ESFs and abnormally low bids criteria (ALBC) gathered in several countries with different tendering approaches. Practical implications concern the optimal design of price scoring rules in construction contract tenders, as well as future analyses of the effects of the ESF and ALBC on competitive bidding behaviour.

Keywords: Bidding; competitiveness; international comparison; scoring rule; tendering

Introduction

Competitive tendering is the conventional method for procuring major construction projects such as building, infrastructure and shipbuilding. The need to guarantee transparency, publicity and equal opportunity in public procurement demands clear procedures to be followed by bidders (de Boer et al., 2001; Falagario et al., 2012) in order to reduce the risk of unfair bias or corruption (Celentani and Gana, 2002; Aurei, 2006).

The simplest, most transparent and effective means of doing this is by what is usually termed the traditional method, in which the contract is awarded to the lowest bidder (Waara and Bröchner, 2006; Wang et al., 2006). This method provides the best motivation for project cost reduction (Bajari and Tadelis, 2001) and predominates in both public and private sectors in the United States (Art Chaовалитвонгсе et al., 2012), Europe (Rocha de Gouveia, 2002; Bergman and Lundberg, 2013) and many other countries worldwide.

Despite its widespread use, however, the traditional lowest bid method is considered by many to be a recipe for trouble (Holt et al., 1994a; Williams, 2003), especially in an oversupplied market (Hatush and Skitmore, 1998; Oviedo-Haito et al., 2014). Factors such as shortage of contracts, difficulties in prescribing and measuring the quality of work, uncertainty of future costs and potential for claims, encourage a situation where the lowest bid is often not the best bid in terms of price (Hatush and Skitmore, 1998; Wang et al.,

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time (Shr and Chen, 2003; Lambropoulos, 2007) and quality (Molenaar and Johnson, 2003; Asker and Cantillon, 2008).

In contrast with the construction industry’s devotion to the traditional method (Palaneeswaran and Kumaraswamy, 2000; Wang et al., 2006), selection of the best price-quality bidder has been promoted for a long time, with early work dating back to 1968 (Simmonds, 1968). This involves also taking non-price or technical/quality factors into consideration in obtaining an optimum outcome for the contracting authority, the owner or the auctioneer (Wang et al., 2013), i.e. the best value for money (Holt et al., 1995). For this, the auctioneer seeks to maximize the owner’s value for a certain budget (price). Generally, this change of paradigm is named best value (BV) in the US (Molenaar and Johnson, 2003) and the most economically advantageous tender (MEAT or EMAT) in the EU and other parts of the world (Bergman and Lundberg, 2013).

In short, the implementation of this awarding approach requires the technical/quality and economic proposals of bidders to be scored and weighed to allow the auctioneer to rank them and identify the most economically advantageous tender. The problem lies in knowing how the economic scoring affects the bidders’ aggressive/conservative behaviour (Ballesteros-Pérez, González-Cruz, Pastor-Ferrando et al., 2012), the bias or unfairness of bidder ranking, or how it even facilitates collusion among competitors (Dini et al., 2006). However, no attempts have been made to date to propose a unified classification of the current economic scoring rules (named here as an economic scoring formula, or ESF) that affect the bid price, to differentiate them from the technical/quality bid factors that are also scored and weighed in order to award a contract (not addressed in this study).

A clear ESF classification or taxonomy is generally a first-order requirement to homogenize ongoing research and allow future developments in almost any discipline, but most likely the countries’ different paradigms concerning bidding and awarding criteria and the traditional common belief considering these rules as ‘given’ and ‘immutable’ might have had a strong influence in keeping such a unified ESF taxonomy from being effectively developed (Ballesteros-Pérez and Skitmore, 2014). Therefore, a taxonomic review is presented of the mathematical expressions for the ESF used in many countries to convert the economic component (bid price) of proposals into scores. In order to do this, a comprehensive review of several countries’ bidding practices is analysed and their common features summarized into a single parametric model that includes both the ESFs themselves along with the abnormally low bids criteria (ALBC) responsible for setting a price threshold for identifying unrealistically low bids. The findings of this research will contribute to improved ESF and ALBC selection by auctioneers in the future and to expand new research, raising awareness about aspects that still need to be treated in scoring rule bidding.

In order to achieve this goal, the paper is organized as follows. The next section provides a literature review structured into two subsections. The first subsection introduces the weighted scoring method, while the second deals with the different components that comprise the scoring rules. In the following section, two important tender aspects are highlighted: the difference between the ranking and scoring rules, and the difference between capped and uncapped tenders. Later, a conceptual framework is proposed in the form of a taxonomic classification, taking into consideration the scoring parameters actually implemented by the ESF; ALBC are also analysed at this point. Finally, a discussion of the results is then included, where an effect deeply related to the ESF mathematical configuration, named apparent or phony economic bid weighting, is also highlighted and studied.

Literature review

Weighted scoring method

Under different denominations, most public international procurement laws and guidelines (e.g. European Union, 2004; United Nations, 2006, 2011; World Bank, 2011; EuropeAID, 2014) provide two main contract awarding approaches, namely: a price-only (lowest price) criterion or weighted multiple criteria (MEAT or BV) (Dini et al., 2006). Generally, the lowest price is recommended for procurement, where the technical specifications or statement of works, as well as bill of quantities, are clear (Dini et al., 2006). On the other hand, a weighted multiple criteria approach is used for more complex procurement where the evaluation requires a number of criteria other than price to be considered and balanced in order to ensure best value for money and where there are different types of scales to be used for the various elements of the offer (Dini et al., 2006). For this reason, these auctions or tenders are often called multi-attribute or multidimensional.

The need for weighting and scoring economic criteria or price-related factors (e.g. life cycle costs, cost of maintenance, decommission costs) along with technical criteria (e.g. compliance, time, availability, quality) is because they are part of a mathematical expression that determines (theoretically) the best return on investment of the procurement of goods, works or services for the owner (Asker and Cantillon, 2010). Whenever a weighted scoring method is implemented, the owner, contracting authority or auctioneer must specify
beforehand in the tender specifications both the criteria and the weights with which the bidders’ proposals will be evaluated. As a general rule, weighted scoring methods can be expressed as:

\[ O_i = \{ W_e \cdot S_i + W_t \cdot T_i \} \delta_i \]

(1)

where:

- \( O_i \) is the overall score achieved by bidder \( i \) (with \( i = 1, 2, ..., N \) bidders) in a tender.
- \( W_e \) is the weight of the economic criteria for tenders for similar projects. In general, \( W_e \) is pre-set by the auctioneer within \( 0 \leq W_e \leq 1 \). When \( W_e = 1 \), the tender is awarded to the lowest price bidder.
- \( S_i \) is bidder \( i \)'s economic score that is calculated according to bidder \( i \)'s submitted economic bid and by means of the ESF pre-set by the auctioneer. For the sake of simplicity, it is assumed here that \( 0 \leq S_i \leq 1 \), but this variable is also usually expressed by a score, for example \( 0 \leq S_i \leq 100 \) points.
- \( W_t \) is the weight of the technical criteria. In general, \( W_t \) is also pre-set by the auctioneer and, since whenever there are no special tender requirements \( W_t = 1 - W_e \), it is also the case that \( 0 \leq W_t \leq 1 \). Analogously, when \( W_t = 1 \) the tender is awarded exclusively according to the technical criteria; these tenders are sometimes called beauty contests (Bergman and Lundberg, 2013).
- \( T_i \) is bidder \( i \)'s technical score that is calculated according to a set of rules, scales or rates for the different attributes that interest the owner or auctioneer. Again, it is assumed that \( 0 \leq T_i \leq 1 \), but this variable can also be expressed as the sum of several technical and/or quality aspects that are also usually scored in points.
- \( \delta_i \) is an abnormality index that equals 1 when bidder \( i \)'s bid is above (more expensive) than the threshold defined by the ALBC, allowing the bidder to compete, and which equals 0 if this condition is not fulfilled. Whenever \( \delta_i = 0 \), bidder \( i \)'s bid is cheaper than the ALBC or, in other words, unrealistically low and, therefore, disqualified. \( \delta_i \) is calculated according to another mathematical expression, named the ALBC, which is generally independent of the ESF.

### Components of the scoring rules

Having defined mathematically the weighted scoring methods, there are four aspects that can be analysed: (a) the way the economic score is calculated (variable \( S_i \), i.e., the ESF); (b) the way the technical score is calculated (variable \( T_i \)); (c) the way the weights are set (relative importance of variables \( W_e \) and \( W_t \) to each other or even the sub-weights within each economic and technical proposal); and, finally, (d) how the ALBC are defined (variable \( \delta_i \)). This study will focus later only on the ESF and ALBC (variables \( S_i \) and \( \delta_i \)).

To date, many researchers have dealt with defining the technical factors, \( T_i \), to be taken into consideration in BV/MEAT selection (e.g. Holt et al., 1994a, 1994b; Palaneeswaran and Kumara, 2000; Shen et al., 2004; Waara and Bröchner, 2006).

With regard to the economic and technical weight values (variables \( W_e \) and \( W_t \)), the most common approach is the linear weighting method (European Union, 2004), where the auctioneer assigns a weight to each criterion in advance. Considered in this way, the issue then becomes one of solving a multi-criteria decision-making problem concerning the weights of several factors (Holt et al., 1994c; Hatunish and Skitmore, 1998; Pongpeng and Liston, 2003; Wang et al., 2013). Furthermore, Jennings and Holt (1998) define multi-criteria decision-making as a ‘selection based on evaluation of tender submissions against criteria predetermined by auctioneers and considered important by them in terms of achieving successful project completion’. Additional techniques have been applied by other researchers, including multi-attribute analysis (Holt et al., 1994b, 1994c), the analytic hierarchy process (Pastor-Ferrando et al., 2010; Wang et al., 2013), fuzzy sets (Nieto-Morote and Ruiz-Vila, 2012), case-based reasoning models (Dikmen et al., 2007), neural networks (Art Chaovilittongse et al., 2012), and data envelopment analysis (Falagario et al., 2012).

However, despite the extensive scientific literature focused on ensuring the best balance of economic and technical weights, the weights to be disclosed in requests for proposals are still currently based on subjective judgments (Lorentziadis, 2010). Fixed criterion weights ensure objectivity and reduce the risk of unfairness and corruption in the evaluation of bidders’ proposals, but only provided they accurately reflect the relative importance of the evaluation factors to the owner. However, it is still possible to create an unfair evaluation system in which too much emphasis is placed on particular evaluation factors, thus favouring (intentionally or unintentionally) those bidders that score highly in the corresponding factors (Lorentziadis, 2010). When weights are subjectively set and fixed before the bid process, the evaluation system is said to correspond to a pre-subjective input model (Pongpeng and Liston, 2003).

Two multi-attribute auction variables remain to be addressed: the economic scoring formula (ESF, variable \( S_i \)) and the abnormally low bids criteria (ALBC, variable \( \delta_i \)) which are the main concern of this paper for, as will be seen later, they can also significantly influence previous variables \( (T_i, W_e \) and \( W_t) \).

The ESF, as already mentioned, is used to translate the bid prices proposed by the bidders into economic scores (Ballesteros-Pérez, González-Cruz, and Cañavate-Grimal, 2012). Auctioneers tend to use
similar or identical ESFs for all their projects but different auctioneers use different ESFs. ESFs also differ between countries. Waara and Bröchner (2006) and Fuentes-Bargues et al. (2014), for example, report a variety of different ESFs used by Swedish municipalities and Spanish public agencies. Nevertheless, in the highly competitive world of construction bidding, the ESF chosen is likely to have significant consequences on the outcome of the auction in terms of aggressiveness (very low bids to win the auction) or conservativeness (higher bids to avoid being disqualified as being unrealistic) of bidders and the outcome of the project (Palaneeeswaran and Kumaraswamy, 2001).

However, very little is known of the relationship between ESFs and other multiple aspects of bidding behaviour. Consequently, ESF selection by auctioneers in practice is invariably a highly intuitive and subjective process (Holt et al., 1994b, 1994c), involving few theoretical or empirical considerations. This produces scoring rules in practice that are often poorly designed (Bergman and Lundberg, 2013) and affected by internal consistency and validity problems (Borchering et al., 1991); this situation is unfortunately shared with other tender documents and leads to cost estimate inaccuracy, claims and disputes (Laryea, 2011).

Therefore, despite the extensive research on competitive bidding over the years (Holt, 2010; Oo et al., 2010), ESF selection is a relatively unresearched area. With very few exceptions, such as Asker and Cantillon (2008, 2010), there is a paucity of research that bridges the gap between the theoretical analyses of abstract scoring rules and their practical application in procurement practice (Bergman and Lundberg, 2013).

Likewise, unrealistically low bids have also received very little attention in the literature to date (Chao and Liou, 2007; Ballesteros-Pérez et al., 2013b). However, when we refer to abnormally low bids criteria (ALBC), we are not focusing on analysing the reason or even the features of bids considered too low to be acceptable. Instead, we refer to how the auctioneer defines mathematically, before receiving the bids, the value below which every bidder will be objectively disqualified when submitting a cheaper bid (Ballesteros-Pérez, González-Cruz, Pastor-Ferrando et al., 2012). For example, some countries define abnormally low bids by the arithmetic deviation from the average bid (International Chamber of Commerce, 2000), even though there is no assurance that such methods accurately identify an actually unrealistically low bid (European Union, 2002; Chotibhongs and Arditi, 2012).

On the other hand, many attempts have been made to propose objective statistical methods to determine the threshold below (or above) which a bid is considered to be abnormal. The problem is that all these methods are useful ex post (after the tender deadline, and therefore not included in the tender specifications). Since everyone acknowledges that statistical methods are open to error and distortion, no successful (objective and indisputable) solution has been found so far (European Union, 2002).

Therefore, the definition of ALBC here only attempts to draw a line that will disqualified low bids; it does not intend to deal with auction rules to discourage collusion, as discussed in depth in the scientific literature (Che and Kim, 2006, 2009; Chowdhury, 2008). ALBC are not always present, but the narrower they are, the more conservative the bids become in order to avoid being disqualified (Ballesteros-Pérez, González-Cruz, and Cañavate-Grimal, 2012; Ballesteros-Pérez et al., 2013a). According to the specifications and procurement guidelines studied, the largest difference between countries lies in ALBC values used.

Therefore, in addressing the problem of ESF and ALBC selection, a conceptual framework in the form of a taxonomic classification for both variables in construction auctions is first proposed, followed by some insights into its use. It is anticipated, therefore, that the findings of this research will contribute to improved ESF and ALBC selection by auctioneers in the future and to expand new research, raising awareness of the aspects still in need of treatment in the bidding scoring rule domain.

**Economic scoring formula (ESF) taxonomy**

In order to create an ESF taxonomy, several notation and methodological aspects need to be addressed to homogenize current knowledge of these scoring rules.

First, a clear difference between a ranking and a scoring rule needs to be established. Ranking rules are used whenever the only awarding criterion is the price, whereas scoring rules are required in multi-attribute tenders to be able to combine their technical and economic components. Mathematical expressions are necessary for the latter kind of rules when it comes to converting the bid values into scores, which is the reason the approach taken is eminently mathematical.

Second, the difference between capped and uncapped tenders needs to be recognized. This involves the setting (capped) or not (uncapped) of a maximum price for bids. It is important to distinguish between these two common bidding approaches as bidders behave differently in each of them, mainly because the ESFs and ALBC are also mathematically different.

Third, a brief explanation is given just before the ESF taxonomy proposal about the international tender sources that allowed the study and review of a varied
array of tender specifications, as well as national and international public procurement economic scoring methods. This aims to show that both the ESF and ALBC taxonomies are not arbitrary, but based on real-life and representative samples.

Fourth, a taxonomy is finally proposed in terms of the variables contained in their mathematical expressions, the so-called scoring parameters (SPs), as these are the only common trait shared across ESFs and ALBC.

Fifth, the interrelationships among SPs in capped and uncapped tenders need to be studied, in order to understand why differences in subsequent bidding behaviour are likely to be due to the implementation of different combinations of SPs in the ESFs and ALBC.

Finally, a brief note is given on how ESFs and ALBC can be represented and that some of their features are better understood graphically when expressed as a function of one of their SPs.

**Ranking versus scoring rules**

When price is the sole criterion in awarding a contract, there is no need to score the bids, since the auctioneer is only interested in ordering or ranking the bids received in terms of their value. There are many ranking rules, including:

- Lowest price, which is the most common in construction procurement (Palaneswaran and Kumaraswamy, 2000).
- Average bid method, in which the awarded bid is the closest to the average bid of all the bid prices for a project (Rocha de Gouveia, 2002).
- Below-average bid method, where the closest to but less than the average bid wins the project (Ioannou and Awwad, 2010).
- Truncated average bid or bid-spread method, where the winning bid is defined as the closest to the average computed after excluding outliers (Waara and Bröchner, 2006).

However, a rank is not enough whenever bid prices are combined with technical criteria, and an ESF is needed to translate a bid price into a numerical score. These latter mathematical expressions form the basis of the taxonomy.

**Capped versus uncapped tenders**

In general, two dominant approaches concerning the price boundaries are identified: capped and uncapped tenders. In uncapped tenders, a bidder $i$ submits an economic bid ($b_i$) which can range from 0 to $+\infty$, unless ALBC are implemented. Conversely, in capped tenders, a bidder $i$ submits a bid that is upper bounded (in price) by the auctioneer and therefore has no option but to equal or underbid this pre-set tender amount ($A$). Bids can therefore range from 0 to $A$, unless ALBC are implemented. Capped tenders also exhibit the property that bids can be expressed in discounts or drops ($d_i$) off $A$, i.e. a bidder $i$'s bid can be expressed as:

$$d_i = 1 - \frac{b_i}{A} \quad \text{or} \quad b_i = (1 - d_i)A \quad (2)$$

Therefore, these discounts or drops can range from 0 to 1 in capped tenders. In addition, for clarification, the pre-set maximum economic tender amount ($A$), is sometimes called the ceiling price in the literature, whereas the term reserve price is identified with ALBC only if stated in the tender specifications (Chowdhury, 2008). Finally, as will be emphasized later, the most important difference between capped and uncapped tenders, beyond the way the bids are expressed, is that their respective ‘scoring parameters’ (variables to be introduced later that configure the ESF and ALBC mathematical expressions) behave in different ways.

**Existing tender practices**

The main goal of the current study is to propose an ESF and ALBC taxonomy, as both ESFs and ALBC constitute the two major components of the economic bid score (variables $S_i$ and $\delta_i$). In order to achieve this, a wide range of ESFs and ALBC in current practice are needed to identify their common features. However, the economic and technical bid weightings that are normally used with ESFs and ALBC ($W_e$ and $W_t$, respectively) are also available for use in identifying shared bidding behaviour trends across countries, and from which the apparent or phony bid weighting phenomenon was deduced as explained later in the Discussion section.

Therefore, in the first instance, a thorough review of tender specifications and national and international public procurement methods was made. This review consisted primarily of the compilation of ESFs and ALBC implemented by contracting authorities or supranational entities (EU and some multilateral agencies) in various countries since, by registering those mathematical criteria it was possible to find common traits, especially among the scoring parameters.

Discipline-related books, several international agencies commissioned reports as well as specific scientific publications also provided very valuable information and these were supplemented by real tendering data provided by multiple international construction contractors working in a wide range of countries.
In terms of books and reports, Ballesteros-Pérez and Skitmore (2014) provide a wide survey of ESFs used in Spain. Waara and Bröchner (2006) and Fuentes-Bargues et al. (2014) cover Swedish and Spanish ESFs respectively currently in use by contracting authorities. Del Cañó-Gochi et al. (2008) analyse and compile the most common procurement approaches and awarding criteria in France, the United States, United Kingdom and Japan. Palaneeswaran and Kumaraswamy (2000) describe a range of different economic factors and systems still in use by public agencies in the United States, Canada and Hong Kong. The European Union (2002) sets a common framework with examples of how each country has customized ESFs and ALBC according to its needs. Furthermore, multilateral agencies’ procurement guidelines, such as those of the World Bank (2011), United Nations (2006), EuropeAID (2014) and the Organisation for Economic Co-operation and Development (2009) were reviewed.

Finally, we obtained a variety of examples of datasets of tender specifications and results from several international construction contractors in countries as diverse as Mexico, Chile, Peru, Colombia, Argentina, Algiers, Morocco, Oman, Egypt, Turkey, Romania, Bulgaria, Australia, New Zealand and China. These tender specifications and bidding results also served the secondary purpose of the study, which was to determine the extent to which particular ESF and ALBC configurations forced bidders to behave in predictable ways.

**ESF taxonomy proposal**

The ESFs are mathematical expressions used to assign numerical scores \( S_i \) to each bidder \( i \)'s bid price. However, these mathematical expressions commonly make use of other sub-variables for converting the price into a score. These sub-variables or scoring parameters (SPs) are usually calculated as a function of the final distribution of bids (Ballesteros-Pérez, González-Cruz, Pastor-Ferrando et al., 2012).

In uncapped tenders, the primary SPs are: the minimum bid \( b_{\min} \), which corresponds to the lowest bid; the maximum bid \( b_{\max} \), which corresponds to the highest bid, the average bid \( b_m \), which corresponds to the average of all bids submitted, and, even though it is uncommon to find it as a variable within an ESF, the number of bidders \( N \) (Ballesteros-Pérez and Skitmore, 2014). As an example, an ESF that gives the maximum score \( 1 \) to the lowest bidder, i.e. \( S_{(1)} = 1 \), and the minimum score \( 0 \) (generally) to the most expensive bidder, i.e. \( S_{(N)} = 0 \), would be written as:

\[
S_i = \frac{b_{\max} - b_i}{b_{\max} - b_{\min}}
\]

In capped tenders, the primary SPs are the same, but expressed in discounts or drops, that is: the maximum drop \( d_{\max} \) corresponds to the lowest bid; the minimum drop \( d_{\min} \) corresponds to the highest bid; the average drop \( d_{m} \) corresponds to the average of all bids (expressed in drops) submitted; and, again, the number of bidders \( N \). The ESF example above can therefore be equally expressed in drops whenever there is a tender amount \( A \) as

\[
S_i = \frac{d_i - d_{\min}}{d_{\max} - d_{\min}}
\]

Apart from the primary SPs, other frequently used measures include the standard deviation of the bids/ -drops \( \sigma \) in uncapped tenders and \( \sigma \) in capped tenders (Ballesteros-Pérez, González-Cruz, Pastor-Ferrando et al., 2012).

As a result, although ESFs may or may not use a SP, in most cases they use at least one SP. Many ESFs were identified in the aforementioned tender specifications and national and international public procurement review. Classifying all these ESFs is similar to classifying different kinds of equations found in mathematics. Therefore, it was considered that the best way to create the taxonomic review was to classify the ESFs according to the SP they actually implemented. The result is shown in Figure 1.

As can be seen, full, dotted and dashed lines represent many combinations of specific mathematical expressions that ESFs may use to assign economic scores to bids. As will also be noted later, the selection of the SPs to be used by each ESF is not trivial and has immediate repercussions on bidders’ competitiveness.

**Scoring parameter (SP) relationships**

To understand how an ESF may produce effects on competitive behaviour, it is necessary to first understand how the SPs actually behave and how they are interconnected. In doing this, several studies have recently made significant advances. Of these, Ballesteros-Pérez, González-Cruz, and Canávalate-Grimal (2012) first proposed a set of equations (specified later in Table 2) that relate each SP to each other in capped tenders with average curve shapes depicted at the bottom in Figure 2 as a function of the SP mean drop \( d_m \). These curved trajectories seem quite logical, taking into account the two boundary price conditions of capped tenders (represented with symbol \( o \) in the graph). These types of tenders are upper-limited by \( A \) and below by \( 0 \), so that, if expressed in drops, bids are \( 0 \leq d_i \leq 1 \). These particular boundaries force the SP to coincide at points \((0, 0)\) and \((1, 1)\), with the exception of \( \sigma \) at \((1, 0)\).
Figure 1 Economic scoring formulae taxonomy as a function of their scoring parameters
### Uncapped Tenders (bids, $b_i$)

- **$S_i$** (1) = 1
- $S_i$ (avg) = 0

### Capped Tenders (drops, $d_i$)

- **$S_i$** (1) = 1
- $S_i$ (avg) = 0

---

**Primary Scoring Parameters (SPs)**

- $b_{\text{min}}$: Minimum bid (lowest bid)
- $b_{\text{avg}}$: Mean bid (average bid)
- $b_{\text{max}}$: Maximum bid (highest bid)
- $d_{\text{max}}$: Maximum drop (lowest bid)
- $d_{\text{avg}}$: Mean drop (average bid)
- $d_{\text{min}}$: Minimum drop (highest bid)

*Secondary SPs, such as N and s or a, have not been considered for the sake of simplicity*

**Independent variables (X-axis)**

- $b_i$: Monetary bid (in uncapped tenders)
- $d_i$: Per-unit drop (in capped tenders)

**Dependent variables (Y-axis)**

- $S_i$: Bidder $i$'s economic score calculated by the Economic Scoring Formula
- $S_{(1)}$: Maximum Score (generally assigned to the lowest bidder and equals 1)
- $S_{(\text{avg})}$: Score assigned to the mean bid $b_{\text{avg}}$ (generally not equals 0.5)
- $S_{(N)}$: Minimum Score (generally assigned to the highest bidder and equals 0)

**Economic Scoring Rule Curves**

- Linear / bi-linear criteria
- Curvilinear criteria

---

**Figure 1 (Continued)**
scoring rules

Figure 2 Major scoring parameter (SP) relationships in capped and uncapped tenders

By understanding the capped SP relationships, it is easy to obtain the uncapped SP relationships too by means of the graph at the top. This is of course a simpler case with only one boundary condition, which is shared with the graph as represented by symbol 0. Therefore the SP in uncapped tenders should follow the linear relationships depicted at the top of Figure 2. These relationships are not deterministic since SPs have statistical variation around their average curves.

However, despite seeming logical, the uncapped SP relationships inferred require a demonstration. In order to do so, Ballesteros-Pérez’s (2010) actual uncapped construction tender database is used. This dataset comprises 45 tenders of design, build and operation of waste water treatment plants and sewage systems contracts from northern Spain awarded between 2007 and 2008. The dataset includes all bidders’ bids from which calculating the SPs mean bid ($b_m$), minimum bid ($b_{min}$), maximum bid ($b_{max}$) and the standard deviation of bids ($s$) is straightforward. The dataset also includes one bidder’s cost estimates ($b_i$) for 14 tenders.

The most representative results of the SP curve calculations can be seen in Figure 3 and Table 1 along with the coefficients of determination ($R^2$). $R^2$ values close to 1 confirm that the SPs’ relationships deduced from the capped tender case point in the right direction.

Furthermore, it is emphasized that the curves depicted in Figures 2 and 3 are expressed as a function of some regression parameters: named $a$, $b$ and $c$ in uncapped tenders, and $a$, $b$ and $c$ in capped tenders. Therefore, by analysing the variation of these regression parameters over time, it is possible to study how aggressively or conservatively the bidders bid in a particular context: with the same ESF and ALBC for instance, or even according to a country’s particular economic situation.

Additional details of how these regression parameters are calculated when a number of $n$ tenders is analysed for capped tenders can be found in Ballesteros-Pérez and Skitmore (2014) and summarized for the first time for both capped and uncapped tenders in Table 2.

This Table, despite representing a collective model (i.e., not taking into account the bidders’ identities), provides an important step towards understanding both the ESF and the way bidders behave in a particular tender.

ESF graphical representation

In order to finish describing the most representative features of an ESF it is worth mentioning that ESFs can be represented in several different ways. The first, which could be called the classic way, consists of representing the ESF variation in a graph with axes expressed in bids $b_i$ or drops $d_i$ (X-axis) and score $S_i$ (Y-axis). This is the kind of representation chosen for the 16 graphs shown in Figure 1.

Another recent approach to represent an ESF is by iso-Score Curve Graphs (iSCG) (Ballesteros-Pérez, González-Cruz, Pastor-Ferrando et al., 2012) in which the $X$-axis usually represents one of the SPs, the $Y$-axis represents any bidder’s bid or drop ($b_i$ or $d_i$), while the curves represent the combination of ($X$, $Y$) points in which the ESF provides the same level of score to a bidder’s bid or drop.

These iSCG have the advantage of showing the whole picture of how any ESF reacts as a function of both the SPs themselves and as a function of the bidders’ past encounters, which suggests applications in competitive bidding issues again and a new way to interpret ESF effects on bidding behaviour.
Abnormally low bids criteria (ALBC)
taxonomy

In parallel with reviewing the prominent features of the ESF and its parameters, the ALBC expressions were also analysed. ALBC have the task of setting a cut-off bid ($b_{abn}$) or drop ($d_{abn}$) that disqualifies any bidder whose bid is cheaper (unless the bidder is capable of justifying this price (European Union, 2004)).

There are several existing systems in use by many countries that are intended to detect abnormally low bids. The most recurring example essentially consists of arithmetic systems that measure the deviation of a particular bid from the average of all bids submitted, with minor differences in the percentage and/or calculation of the average (for instance Belgium, France, Italy, Portugal, Spain and Greece use ranges mostly varying between 10% and 15%) (European Union, 1999). However, as the EU Commission reports (European Union, 1999), there is to date no systematic method that enables the effective evaluation of ALBC in EMAT or BV auctions, since the systems currently in use are recognized to be of limited efficacy.

Of the tender specifications analysed, six generic ALBC were identified. Some are applicable to capped tenders only and others apply to both capped and uncapped tenders. Basically, there are two groups of ALBC: those that make use of a SP (only cases of $b_{m}$, $d_{m}$, $s/\sigma$ and $N$ have been found), and those that do not make use of any SP and, therefore, the cut-off limit does not depend on the final bid distribution. In these ALBC, the cut-off economic limit can be known in advance, that is, before the tender deadline. This also happens with the ESF: whenever no SP is used (case 6 in Figure 1), the ESF is totally predictable and unmovable, no matter what final bids are submitted.

The six ALBC, the first four of which are expressed as a function of one SP and the last two as a function of no SP whatsoever, are then:

$$b_{abn} = (1 - \varepsilon) b_{m}$$
Possible in both capped and uncapped tenders. Basically, it is the most common criterion in EU countries, with a parameter $\varepsilon$ that is usually set between 0.05 and 0.20. Any bid that fulfils the condition $b_{i} < b_{abn}$ will be ruled out as inadmissible

$$d_{abn} = (1 + \theta) d_{m}$$
Possible in capped tenders only. This uses a multiple of the average drop such that all bidders with a higher drop ($d_{i} > d_{abn}$) will be not considered. Parameter $\theta$ also usually ranges between 0.05
### Table 1  Scoring parameter relationship calculations for the uncapped construction tender dataset

**Actual scoring parameter (SP) values from the original 45 tenders**

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(Continued)
and 0.20. Perhaps, as found many times in the literature, it is interesting to point out that, whenever the expression of $d_{abn}$ comes from the translation of the previous ALBC as a function of $\varepsilon$, then $d_{abn} = 1 - (1 + \varepsilon)(1 - d_m)$

Possible in both uncapped (under the expression on the left) and uncapped tenders (under the translated expression $d_{abn} = d_m + \lambda \sigma$). It sets a threshold in bid or drop standard deviation multiples, beyond which all bidders are disqualified.

Parameter $\lambda$ usually ranges between 0.5 and 2

Possible for capped and uncapped tenders. Basically, this criterion directly eliminates a proportion $\mu$ of bidders just for being located at the extremes (in one or in both extremes lowest and highest). $\mu$ usually ranges between 0.05 and 0.25. Finally, there is another variation of this criterion by which a pre-set number of bidders ($N_{abn} = \eta$) is disqualified (no matter how many bidders are actually competing)

Useful for capped and uncapped tenders. This makes no use of SP so it is a deterministic cut-off limit for a particular economic amount the auctioneer considers too low to be acceptable. As happens with the rest of ALBC expressions, this limit has to be included in the tender specifications, otherwise it does not comply with the principles of transparency, publicity and equality of opportunity. Parameter $\omega$ is generally chosen depending on the particular tender economic volume and/or the engineer’s estimate

Similar to the previous ALBC, but only applicable for capped tenders. This sets a drop value above which any bidder’s drop will be disqualified. Parameter $\delta$ is generally set within the range 0.10 to 0.30
Table 2  Mathematical relationships of scoring parameters (SP) in capped and uncapped tenders

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<th>Capped Tenders</th>
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<td><strong>Regression coefficients</strong></td>
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<td>Maximum drop (lowest bid)</td>
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<td>(potential expression)</td>
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<td>(Parabolic relationship expressions are also found in Ballestros-Pérez et al. (2012a))</td>
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<td>($N$ is the average of the participating bidders in the $n$ past tenders analyzed)</td>
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<td>$est \ d_o = 1 + \gamma(d_m - 1)$</td>
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<td>(This expression is commonly used the other way around, i.e., as a function of $b_o$ which actually is the Forecasting Parameter)</td>
<td>(This expression is also commonly used the other way around, i.e., as a function of $d_o$)</td>
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<tr>
<td>(bid aggressiveness</td>
<td>(bid aggressiveness)</td>
</tr>
</tbody>
</table>
All these ALBC are interconnected, that is, it is possible to find a mathematical equivalency between the proportion of bidders disqualified in the first four ALBC (the ones that use a SP) and between the last two ALBC (the ones that make no use of any SP). This equivalency has been proposed in the Appendix by means of Tables A1 and A2, respectively. However, those calculations require knowing the exact bid probability distribution function, which has been an unsolved and ongoing research bidding topic over the years. In this connection Skitmore (2013) reports some of the most common found in the scientific literature, such as uniform, normal, lognormal, gamma and Weibull. For a first approach, however, Tables A1 and A2 assume a simple uniform distribution.

A relevant practical note concerning ALBC found during the tender review was that, when competing with ALBC mathematical expressions that make no use of SPs (expressions $b_{\text{abn}} = \omega$ and $d_{\text{abn}} = \delta$), most bids tend to be close to the cut-off limit ($\omega$ or $\delta$), apparently sacrificing bigger profits.

Mathematically this can be simply explained for uncapped tenders as, when $b_m \rightarrow \omega$, therefore, $b_{\text{min}} \rightarrow \omega$ (otherwise the lowest bidder is directly disqualified) and the maximum bid has no option but $b_{\text{max}} \rightarrow \omega$. Then, since $b_{\text{max}} - b_{\text{min}} \rightarrow 0$, so does the standard deviation $\sigma \rightarrow 0$. Analogously, $N_{\text{abn}} \rightarrow 0$ (because everyone knows where the cut-off limit is located), therefore, $b_m$ is stuck near $\omega$ making it impossible to establish a statistical relationship with the rest of ALBC which make use of SPs (first four shown in this section).

In capped tenders, a similar reasoning process may arise: $d_m \rightarrow \delta$ and so do $d_{\text{max}} \rightarrow \delta$ and $d_{\text{min}} \rightarrow \delta$, forcing $\sigma \rightarrow 0$, whereas $N_{\text{abn}} \rightarrow 0$ as well.

This situation has immediate practical repercussions since it constitutes the first empirical proof that when bidders can accurately calculate the risk of being disqualified (because they know in advance where exactly $\omega$ or $\delta$ are), most will place their bids just before crossing that extreme. In this way, bidders avoid losing as much economic score as possible, despite frequently relinquishing more profits compared to situations in which the ALBC depend on a SP and the final position of the cut-off limit is not known in advance.

**Discussion**

In addition to the review of tender specifications, literature and public procurement methods allowing the ESF and ALBC taxonomies to be created, several other interesting issues on bidding behaviour have emerged. For example, how SPs relate to each other (summarized in Table 2), how bid distribution concentrates near the cut-off limit when the ALBC make no use of SP, and how the ALBC are mathematically interconnected (shown in the Appendix). Another recurrent effect of apparent or phony economic bid weighting takes place whenever a percentage of the economic score ($S_i$) is either never achievable or always awarded.

To introduce this phenomenon, suppose the economic and technical bid weightings in a tender are balanced ($W_e = W_t = 0.5$) and that the tender specifications adopt an ESF that gives away 0.30 (out of the total 1.00) no matter the bid or drop the bidder is submitting. An example of this ESF would be:

\[
S_i = 0.30 + 0.70 \frac{b_{\text{max}} - b_i}{b_{\text{max}} - b_{\text{min}}} \quad \text{or} \quad S_i = 0.30 + 0.70 \frac{d_i - d_{\text{min}}}{d_{\text{max}} - d_{\text{min}}}
\]

In this case, bidders can only compete to achieve an economic score from 0.30 to 1.00. In other terms, the following fraction of the overall score, $O_\beta = 0.30 \cdot W_e = 0.30 \cdot 0.5 = 0.15$ is not disputed. If this happens, the true economic bid weighting ($W_{e,\text{t}}$) is not now 0.5, but $W_{e,\text{t}} (1 - 0.30)$ out of the overall possible score $W_{e,\text{t}} (1 - 0.30) + W_t$, that is,

\[
W_{e,\text{t}}(1 - 0.30) + W_t = \frac{0.5 (1 - 0.30)}{0.35} \approx 0.412
\]

which forces the true technical bid weighting ($W_{t,\text{t}}$) to be $1 - W_{e,\text{t}} \approx 1 - 0.412 = 0.588$, instead of 0.5. This is a significant deviation from the situation in which the weightings were intended to be balanced.

This phenomenon can be generalized, even for the technical bid weighting, and takes place not only whenever a fraction of the economic score ($Q$) is given away by the ESF, but also when a fraction of the score is unreachable mathematically or at least unreachable (undisputed) in normal conditions of competitiveness. In these cases, the general expression for calculating the true economic bid weighting is:

\[
W_{e,\text{t}} = \frac{W_e (1 - Q)}{W_t + W_e (1 - Q)}
\]

If $W_t = 1 - W_e$ then,

\[
W_{e,\text{t}} = \frac{W_e (1 - Q)}{(1 - W_e) + W_e (1 - Q)} = \frac{(1 - Q) W_e}{1 - Q W_e}
\]

where:

- $W_e$: is the original economic bid weighting (in per-unit values) stated in the tender specifications.
- $W_{e,\text{t}}$: is the true economic bid weighting (in per-unit values) with $W_{e,\text{t}} \leq W_e$ always.
- $Q$: is the fraction of the economic score either rarely or almost always achievable (in per-unit values).
$W_t$ is the original technical bid weighting (in per-unit values) stated in the tender specifications.

$W^*$ is the true technical bid weighting (in per-unit values) with $W^* = 1 - W_t$.

A representation of Equation 4 can be found in Figure 4 for all the intervening variables.

Using the diagram above is quite simple. Generally, the user must enter by the lower X-axis through analyzing the ESF and estimating $Q$, then select the curve $W_e$ corresponding to the value stated in the tender specifications and find the position of the vertical intersection with which to obtain the true economic ($W_e$) and technical ($W^* = 1 - W_t$) bid weighting values on the left and right, respectively.

Practical implications of both Equation 4 and Figure 4 are evident. If tender specifications implement ESFs with mathematical expressions that do not allow awarding the whole range of economic scores (from 0 to 1) to the competing bidders, the economic and technical bid weightings will become increasingly reversed ($W_e$ will lose actual weight in favour of the technical bid weighting $W_t$) as the fraction of undisputed economic score increases. This situation could mislead bidders' strategies, or even be used (intentionally or unintentionally) by the contracting authorities to give the appearance of applying some economic and technical bid weightings while actually applying different ones.

However, perhaps, the most difficult issue is to estimate $Q$, since not all ESFs are as simple as the one provided in the example. For this purpose, the bidders or contracting authorities can make use of the SP estimated cost bid ($b_o$) or drop ($d_o$) from a future tender for forecasting the rest of SP (by means of Table 2) and, with these values, calculate the final ESF curve, with which observing $Q$ is trivial.

In general, any owner or auctioneer, when designing and implementing a new ESF for future tender specifications should bear in mind that the ‘whole range’ of possible scores (from 0.00 to 1.00) must always be actually achievable by the bidders in normal conditions of competitiveness. Nonetheless, strictly speaking, this can only be possible by implementing an ESF under cases 4 or 5 of the ESF taxonomy in Figure 1, since they are the only ones that award the maximum score ($S_{max} = 1$) to the lowest bidder (that is, to SP $b_{min}$ or $d_{max}$) and the minimum score ($S_{min} = 0$) to the highest bidder (that is, to $b_{max}$ or $d_{min}$). From this last statement, it is clear that specific ESFs that make no use of any SP (case 6 in Figure 1) are the most vulnerable to apparent economic bid weighting.

However, the problem with cases 4 and 5 is that these ESFs are the most vulnerable to collusion, particularly cover-bidding, in which bidding rings can greatly condition the final economic scores (by submitting extremely high and/or low bids for pushing the rest of the bidders’ scores towards the average, thus also paradoxically diminishing the economic bid weighting).

In this sense, all the combinations of SPs from Figure 1 would actually require ALBC to be implemented for both the high and lower extremes of the bid distribution with the simultaneous aim of avoiding...
bid-covering. The key is how to set the right ALBC width: narrow enough to make collusion difficult, but not so narrow so as to reject bids that are actually competitive and truthful. Obviously, the problem of reaching the perfect configuration and combination of ESF and ALBC still requires further research, but has now acquired a new dimension by highlighting how apparent or phony bid weighting is also an important effect to be considered in seeking a solution.

Conclusions

Whenever there is need for converting price bids into scores for combination with technical proposal attributes, such as quality or client’s preferences (like MEAT and BV), mathematical criteria need to be included in the tender specifications. The classification of these mathematical criteria, named economic scoring formulas (ESFs) and abnormally low bids criteria (ALBC), constituted the main aim of the present study.

By going through their taxonomies it is clear that there are many ESFs and ALBC currently in use for evaluating price bid proposals in construction auctions and they affect bidding behaviour in profound ways, most of which are little understood. As a result, their design in practice is invariably a highly intuitive process, involving few theoretical or empirical considerations.

In this paper, several outcomes relating to ESFs and ALBC have been considered and analysed. After a wide but thorough review of international tender specifications along with multiple other sources such as international public procurement guidelines and scientific articles and books on the topic, new ESF and ALBC taxonomies have been proposed. These taxonomies will enable expanding research in the near future while establishing a reasonable degree of homogeneity concerning nomenclature and denominations.

Furthermore, because of classifying the ESF and ALBC according to their scoring parameters (SPs) actually used, their relationships have now been adduced for uncapped tenders (tenders without an upper-price limitation). This will be useful for analysing changes or habits in bidding behaviour in upcoming research since they can accurately depict recurring statistical information on tenders.

Additionally, several other results derived from the ESF and ALBC taxonomies have been obtained. For example, it has been explained how bid distribution concentrates near the cut-off limit when the ALBC makes no use of a SP, as well as how ALBC are actually mathematically interrelated whenever a SP is used.

Finally, apparent or phony economic bid weighting explains how the economic bid weighting is actually overestimated whenever an ESF does not assign the whole range of scores to all the participating bidders. This phenomenon is quite common in ESF in real practice and has to be avoided when designing both ESFs and ALBC.

From the several examples provided in the paper, it is clear that previous research on auction design is still very far from incorporating important practical issues, some of which have been described here. The main contribution here is a compilation and perhaps a first step towards a new approach in bidding analysis useful to both auctioneers and bidders. This is especially the case with the former when designing or selecting a particular combination of ESF and ALBC for the tender specifications. However, the present analysis is mostly restricted to providing a general qualitative picture. The next logical research step will be the development of a quantitative means for determining, and hence controlling, the effect of small variations in the ESF and/or ALBC mathematical expressions on, for instance, the level of bidders’ aggressiveness/conservativeness in a future tender. Taken together with the risk attitudes of the individuals involved, a new door is opened for the possibility of personalized optimal price scoring rules in construction auction design.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

CONICYT Program Initiation into Research 2013 [grant number 11130666].

Note

1. To avoid confusion, the terms ‘auction’ and ‘tender’ will be used here as synonymous, as well as ‘auctioneer’, ‘client’, ‘owner’ and ‘contracting authority’. Strictly speaking, the words ‘construction auctions’ in this study do not refer to ‘classical auctions’ where the highest bidder often wins, but actually refer to ‘procurement auctions’ or ‘reverse auctions’, which are a common type of auction in which the roles of the buyer (client, owner, auctioneer or contracting authority) and the seller (bidders or tenderers) are reversed with the primary objective to drive purchase prices downward.

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Appendix

The following tables allow the conversion of one criterion of the ALBC to another assuming the bid distribution follows a uniform distribution, which constitutes a simplification of the reality. Depending on which is the known ALBC expression, locate that column and go down until reaching the same row where the text ‘independent variable’ can be read. The
For the interested reader, mathematical proofs (1–10) of Tables A1 and A2 can be found as Supplemental online material.

**Table A1**  Mathematical relationships among abnormally low bids criteria (ALBC) with scoring parameters (SPs)

<table>
<thead>
<tr>
<th>Scoring rules</th>
<th>( b_{abn} = (1 - \varepsilon) b_m )</th>
<th>( d_{abn} = (1 + \theta) d_m )</th>
<th>( b_{abn} = b_m - \lambda \cdot s )</th>
<th>( d_{abn} = d_m + \lambda \cdot \sigma )</th>
<th>( N_{abn} = (1 - \mu) \frac{N}{2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generally:</td>
<td>( 0 \leq \varepsilon \leq 1 )</td>
<td>( 0 \leq \theta \leq \frac{1 - d_m}{d_m} )</td>
<td>( 0 \leq \lambda \leq \frac{b_m}{s} ) or ( \frac{1 - d_m}{\sigma} )</td>
<td>( 0 \leq \mu \leq 1 )</td>
<td>( 0 \leq \mu \leq 1 )</td>
</tr>
<tr>
<td>(from tougher to softer)</td>
<td>(from tougher to softer)</td>
<td>(from tougher to softer)</td>
<td>(from tougher to softer)</td>
<td>(from tougher to softer)</td>
<td></td>
</tr>
<tr>
<td>Actual mathematical limits:</td>
<td>(-\infty &lt; \varepsilon \leq 1 )</td>
<td>(-1 &lt; \theta \leq \frac{1 - d_m}{d_m} )</td>
<td>(-\infty &lt; \lambda \leq \frac{b_m}{s} )</td>
<td>(-1 &lt; \mu \leq 1 )</td>
<td></td>
</tr>
<tr>
<td>( \varepsilon = 0 ) disqualifies ( N/2 ) bidders</td>
<td>( \theta = 0 ) disqualifies ( N/2 ) bidders</td>
<td>( \lambda = 0 ) disqualifies ( N/2 ) bidders</td>
<td>( N_{abn} = 0 ) if ( \varepsilon \geq \frac{N + 1}{2} ) ( b - a )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \varepsilon = \frac{A - b_m}{b_m} \cdot \theta \]  
\[ \theta = \frac{b_m - \varepsilon \cdot A}{T - b_m} \]  
\[ \lambda = \frac{N - 1}{N + 1} \cdot \frac{2 \varepsilon \sqrt{3}}{b - a} \]

\[ \varepsilon = \frac{N + 1}{N - 1} \cdot \frac{b - a}{2 \sqrt{3}} \]  
\[ \theta = \frac{N + 1}{N - 1} \cdot \frac{d_m^a - d_m^b}{d_m} \cdot \frac{\lambda}{2 \sqrt{3}} \]  
\[ \lambda = \frac{N - 1}{N + 1} \cdot \frac{2 \theta d_m}{d_m^a - d_m^b} \]  
\[ \mu = \frac{\lambda}{\sqrt{3}} \]  

\[ \varepsilon = \frac{N + 1}{N - 1} \cdot \frac{b - a}{2} \cdot \mu \]  
\[ \theta = \frac{N + 1}{N - 1} \cdot \frac{d_m^a - d_m^b}{2 d_m} \cdot \mu \]  
\[ \lambda = \mu \sqrt{3} \]  
\[ \mu = \frac{\lambda}{\sqrt{3}} \]  
\[ N_{abn} = 0 \] if \( \lambda \geq \sqrt{3} \)  
\[ 0 < N_{abn} \leq \frac{N}{2} \] if \( 0 \leq \lambda < \sqrt{3} \]  
\[ N_{abn} = 0 \] if \( \theta \geq \frac{N + 1}{2} \) \( d_m^a - d_m^b \)  
\[ 0 < N_{abn} \leq \frac{N}{2} \] if \( 0 \leq \theta < \frac{N}{2} \]  
\[ N_{abn} = 0 \] if \( \lambda \geq \sqrt{3} \)  
\[ 0 < N_{abn} \leq \frac{N}{2} \] if \( 0 \leq \lambda < \sqrt{3} \]
Table A2  Mathematical relationships among abnormally low bids criteria (ALBC) without scoring parameters (SPs)

<table>
<thead>
<tr>
<th>$b_{abn} = \omega$</th>
<th>$d_{abn} = \delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq \omega \leq +\infty$ (from softer to tougher)</td>
<td>$0 \leq \delta \leq 1$ (from tougher to softer)</td>
</tr>
<tr>
<td>$\omega$ (independent variable)</td>
<td>$\delta = 1 - \frac{\omega}{A}$</td>
</tr>
<tr>
<td>$\omega = (1 - \delta) A$</td>
<td>$\delta$ (independent variable)</td>
</tr>
</tbody>
</table>