

Equality in Cumulative Voting: A Systematic Review with an Improvement Proposal

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Abstract

Context. Prioritization is an essential part of requirements engineering, software release planning and many other software engineering disciplines. Cumulative Voting (CV) is known as a relatively simple method for prioritizing requirements on a ratio scale. Historically, CV has been applied in decision-making in government elections, corporate governance, and forestry. However, CV prioritization results are of a special type of data—compositional data.

Objectives. The purpose of this study is to aid decision-making by collecting knowledge on the empirical use of CV and develop a method for detecting prioritization items with equal priority.

Methods. We present a systematic literature review of CV and CV analysis methods. The review is based on searching electronic databases and snowball sampling of the found primary studies. Relevant studies are selected based on titles, abstracts, and full text inspection. Additionally, we propose Equality of Cumulative Votes (ECV)—a CV result analysis method that identifies prioritization items with equal priority.

Results. CV has been used in not only requirements prioritization and release planning but also in e.g. software process improvement, change impact analysis and model driven software development. The review presents a collection of state of the practice studies and CV result analysis methods. In the end, ECV was applied to 27 prioritization cases from 14 studies and identified nine groups of equal items in three studies.

Conclusions. We believe that the analysis of the collected studies and the CV result analysis methods can help in the adoption of CV prioritization method. The evaluation of ECV indicates that it is able to detect prioritization items with equal priority and thus provide the practitioner with a more

fine-grained analysis.

Keywords: Cumulative voting, prioritization, requirements engineering, compositional data, log-ratio

1. Introduction

Software products are becoming larger and more complex. Each product is usually affected by a large number of factors such as functional requirements, quality attributes, or software process improvement issues. Since time, funding, and resources are limited, it is seldom possible or even desirable to fully address all the factors. Therefore, the level of attention to a particular factor should be decided according to its importance (e.g. business value), cost, risk, volatility, dependencies between the factors and other such criteria. These type of decisions are made by product stakeholders: users, clients, managers, sponsors, developers, and other persons associated with the product. In order to make decisions regarding a large number of factors it is highly advisable to prioritize the factors in a systematic way [1].

Prioritization is commonly used in requirements selection and release planning. First, project stakeholders prioritize software requirements. Priority values then can be used to determine the order in which the requirements are going to be implemented. Requirements with higher priority could be implemented early while requirements with lower priority may be postponed for later releases or left out.

Another example could be prioritization of potential security threats. It is done by security professionals, software developers and system administrators to assess the level of risk and to select risk mitigation activities.

One of the prioritization methods used in software engineering is Cumulative Voting (CV) [2]. The main advantage of CV is that it is relatively simple and fast, yet produces priorities in ratio scale [1, 3]. This allows us to not only determine what prioritization items are more important but also how much more important they are. (Ratio scale prioritization is particularly important in software release planning and cost-value analysis [4, 5].)

Prioritization is usually performed by multiple stakeholders where individual priorities are combined into a single priority list. Each stakeholder's preferences may have different weight in the final priority. Such prioritization provides more information than just the priorities of factors. In the end, it may be useful to analyze the results of the prioritization to assess disagree-

ment between stakeholders, measure stakeholder satisfaction with the results or find distinct groups of stakeholders.

The purpose of this study is to help industry practitioners and academia researchers in adopting, using and developing CV, while the importance of prioritization in software engineering and the prospectiveness of CV constitutes a need to do further research in this area.

This study presents a systematic literature review on the empirical use of CV and CV result analysis methods. CV results correspond to special type of data—compositional data. Principles of compositional data analysis are described in this paper. A new method for CV result analysis, called Equality of Cumulative Votes (ECV), is proposed. The method identifies prioritization items with *equal* priority. ECV is evaluated using a considerable amount of data, which was obtained from the primary studies identified by the systematic review (through the kindness of the authors of said studies).

The remainder of this paper is structured as follows. We introduce definitions and place this study in a context in the next section. In Section 3 we give a short presentation of related studies. In Section 4 research questions and the methods used in this study are presented. In Section 5 the execution of the systematic literature review (SLR) is presented; however, we wait with presenting the results of the SLR. In Section 6 the design of our method of analysis, Equality of Cumulative Votes (ECV), is given, while the results of the SLR and the corresponding evaluation of ECV are presented in Section 7. Section 8 provides discussions, presents threats to validity and concludes the paper.

2. Background

This section presents definitions and places this study in a context. In the coming sections we will cover: a description of software requirements prioritization methods; examples of CV result analysis methods; and a description of compositional data analysis and CV.

2.1. Prioritization Methods

Some of the most popular prioritization methods are the analytical hierarchy process (AHP), cumulative voting (CV), ranking, numerical assignment, top-ten, the planning game, minimal spanning tree, bubble sort and binary search tree [1, 6]. Ranking and numerical assignment methods perform prioritization on an ordinal scale. AHP and CV are, on the one hand, considered

to be harder to use and also more time consuming compared to other methods but, on the other hand, produce priorities in ratio scale.

Ratio scale priorities have several advantages over ordinal scale priorities. Ratio scale shows not just the order of items but also relative distance between them. This enables the priority of a group of items to be calculated by summing up the priorities of individual items [4]. It is possible to say that one item or set of items has higher priority than another set of items. Supposing stakeholders have to choose between several low priority items and one item with higher priority; with ordinal scale, the item with highest priority will always be selected first. However, if priorities are given on a ratio scale, it is possible that lower priority items will be selected if their cumulative priority is higher.

Finally, the ratio scale allows the combining of multiple priority factors by calculating ratios between them. One example of this is the cost-value ratio that shows which requirements give more value for less money [5].

2.2. Prioritization Result Analysis

Disagreement between stakeholders happens when two or more stakeholders have assigned a different priority to one prioritization item. If the level of disagreement is high it may indicate potential conflicts between stakeholders. Such conflicts may be of technical character, as well as social or cultural.

The satisfaction a stakeholder has with the final prioritization results is determined by the difference between the results and the individual priorities of the stakeholder. A smaller level of difference leads to higher satisfaction. In the end, stakeholder satisfaction is important because it is necessary to achieve stakeholder commitment.

In some cases a part of stakeholders may form a group of some kind and, therefore, prioritize requirements similarly. It may be useful to detect whether a group of stakeholders has different preferences compared to other stakeholders. As an example, in [7], domain experts, technical experts, managers, project managers, testers, and developers use CV to prioritize software process improvement issues and the CV results are analysed using disagreement charts and satisfaction charts. Finally, principal component analysis (PCA) is used to identify distinct groups of stakeholders.

The same items can be prioritized by the same stakeholders multiple times from different perspectives. In this case it is useful to determine correlation between the priorities in different perspectives to assess the differences between the perspectives. As an example, in [8], CV is used by developers,

105 testers and managers to prioritize quality attributes. The same quality at-
106 tributes are prioritized from two perspectives: the perceived situation today
107 and the perceived ideal situation. Correlation between the two perspectives
108 is evaluated using the Spearman rank correlation matrix. This allows an
109 analysis of how well the company balances the priorities of software quality
110 attributes.

111 In [9] change impact issues are prioritized by developers, testers, man-
112 agers, and system architects. The prioritization is done with respect to three
113 perspectives: strategic, tactical, and operative. In order to determine corre-
114 lation between the perspectives, CV results are analyzed using the Kruskal-
115 Wallis test. In [10] the results of [9] are further analyzed using PCA, bi-plot,
116 and ternary plot. In this case, PCA is used to find correlated issues, bi-
117 plot shows variance, correlation, difference between the priorities of issues,
118 and the viewpoints of stakeholders, while ternary plots are used to show the
119 relative number of issues that received high, medium, and low priority.

120 As can be seen above, from the examples above, prioritization has been
121 performed with various stakeholders, using different perspectives and, in the
122 end, also analyzed using various techniques. We will next describe in more
123 detail one of the more common methods to manage prioritization issues—
124 cumulative voting—which has been used in software engineering for some
125 time. (CV has its roots in corporate governance and biology.)

126 2.3. Cumulative Voting

127 CV is a prioritization method for prioritizing a list of items [2] and has
128 been studied and applied in various fields.

129 In forestry it is used to take into account opinions of different parts of
130 society while planning forest harvesting [23]. CV has also been used as a
131 voting mechanism in government elections [24] and to aid decision making
132 in corporate governance [12]. In computer science we have seen CV being
133 part of various software algorithms, e.g. in [25] it is used as part of pattern
134 detection algorithm that is used to locate the optic nerve in a retinal image.

135 In software engineering CV has been applied not only in requirements
136 engineering and software release planning [26] but also in software security
137 [27], software quality [8], software metrics [28], software process improvement
138 [7], and software verification and validation [29].

139 Studies have also used CV as part of a research method itself. For in-
140 stance, in [30] software impact analysis issues are elicited in structured in-
141 terviews and afterwards the importance of each issue is determined with the

142 help of CV. Whether CV has been used in a particular domain or as part of
143 a methodology is in itself quite irrelevant as long as one takes into account
144 the type of data CV results consist of.

145 CV has many synonyms in literature: hundred (100) dollar (\$) method/
146 test and hundred (100) point method.

147 In CV a stakeholder is given 100 points, imaginary dollars or units of
148 percentages that can be spent on the prioritization items. In the simplest
149 case, the stakeholder can spend any amount of points on any number of items
150 as long as the total amount adds up to 100. The more points assigned to an
151 item, the higher the priority of the item (and implicitly, the lower priority
152 to the other items). The stakeholder may spend all points on just one item
153 or distribute them among all or some of the items. Once again, this is the
154 simplest case; other variants exist, which we will see next.

155 Often prioritization is done by more than one stakeholder. The final prior-
156 ity of an item can be calculated by adding up the points each stakeholder has
157 spent on it. Sometimes the vote of some stakeholders may be more important
158 than the votes of others. For example, a manager may be more influential or
159 shareholders may have different amount of shares. In such a case the prior-
160 ities of each stakeholder may be multiplied by an individual coefficient or a
161 stakeholder may be given a more points to perform the prioritization.

162 Worth mentioning in this context is that it is advisable to randomize the
163 order of items in a prioritization list. This is necessary in order to minimize
164 the effect of order on the prioritization results, which has shown to have an
165 effect [16].

166 2.3.1. *Benefits and Drawbacks of Cumulative Voting*

167 Compared to analytical hierarchy process (AHP), CV is faster and easier
168 to learn and use [1, 3]. AHP benefits from consistency check, but CV does
169 not require this because all prioritization items are evaluated simultaneously
170 [3].

171 There are, however, a few problems with CV. First of all, it cannot be
172 repeated for the same stakeholders and prioritization items due to stakeholder
173 bias [2] (c.f. Section 2.3.4). Secondly, CV becomes more difficult to use when
174 the number of prioritization items increases [17].

175 2.3.2. *Example of Cumulative Voting with Several Stakeholders*

176 Let us next give an example of CV with several stakeholders. Suppose
177 Robin, Alice, and John are three friends who want to buy some beverages in

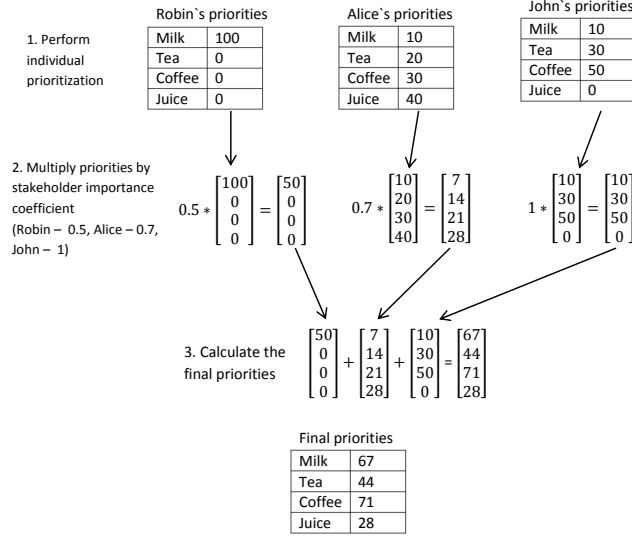


Figure 1: Example of CV with several stakeholders.

178 a store. They have different preferences but do not want to buy too many
 179 drinks. Therefore, they decide to use CV to decide what to buy. Each of
 180 the friends distributes 100 points between four items: milk, tea, coffee, and
 181 juice (Step 1 in Figure 1). In this case each of them will spend a different
 182 amount of money on the purchase, hence, their priorities are multiplied by
 183 different coefficients (Step 2 and the stakeholder importance coefficient in
 184 Figure 1). The final beverage priorities are calculated by summing up the
 185 weighted priorities of stakeholders (Step 3 in Figure 1).

186 2.3.3. Stakeholder Bias

187 Prioritization using CV may be biased if a stakeholder knows the pref-
 188 erences of other stakeholders. She may manipulate the results by spending
 189 more points on items that are important to her but not to the other stake-
 190 holders. On the one hand, stakeholder bias makes it unreasonable to repeat
 191 CV with the same prioritization items and stakeholders. On the other hand,
 192 this property of CV may be useful in giving more power to important mi-
 193 nority stakeholders, such as security experts or software testers. Suppose the
 194 same software requirements are prioritized for a second time using CV. A
 195 developer might know that all vital functionality is selected by other stake-
 196 holders, but his toy feature is left out. In effect, the developer could spend

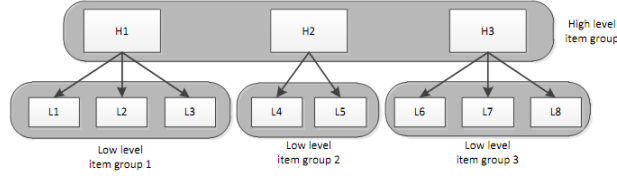


Figure 2: Example of prioritization item hierarchy.

all his points on this feature to put it in the next release.

Stakeholder bias may be mitigated by setting a maximum priority that can be assigned to an item. This way each stakeholder is forced to distribute the money between several prioritization items [4].

Another bias is that people in general tend to assign round priority values. This is likely caused by lack of objective judgement criteria. Either way it seems to be a problem not acknowledged by many since all prioritization is largely based on expert opinion.

2.3.4. Scalability of Cumulative Voting—Hierarchical Cumulative Voting

The standard CV approach has a low scalability. If the number of prioritization items is high, stakeholders may lose sight of the bigger picture and assign priorities to a limited number of items. One, unsophisticated, solution to the problem is to provide more points for prioritization (1,000 or 10,000 instead of 100); however, one could take another approach.

When the number of prioritization items is high they can usually be grouped hierarchically by forming a tree structure (Figure 2) and, thus, parent-child dependencies will exist between many items.

In [4] the authors propose a method for prioritizing hierarchically structured items called Hierarchical Cumulative Voting (HCV). It may be seen as combination of the hierarchical part of the Analytical Hierarchy Process (AHP) [1, 18] and the CV prioritization method. Since items are prioritized in smaller sets, stakeholders do not lose sight of the bigger picture during prioritization, and the prioritization of a large number of requirements is considered easier.

2.3.5. Compensation Factors

HCV deals with the problem of prioritization scalability but it comes at a cost. Low level item groups may consist of different numbers of items, but the number of points spent on each group is the same, i.e. in a small-sized

group, the same amount of points is distributed among fewer items. Hence, items in smaller groups are statistically more likely to have a higher priority, on average, compared to items in larger groups. To balance this difference each low level prioritization item can be multiplied by a compensation factor [4].

As an example, suppose an item (A) in a group of 10 items is assigned 60 points. Hence, A will receive 600 compensated points. In this case it is impossible for any item in a group smaller than 6 items to compete with A . Even if item (B) in a group of 5 is assigned the maximum number of points (100), the maximum compensated priority value B can receive is 500.

In [17] the authors suggest that compensated prioritization is more favorable compared to uncompensated. But neither compensated nor uncompensated prioritization is perfect and, as a general rule, it is better to keep the size of prioritization item groups similar.

2.3.6. HCV Execution

According to [4], HCV is conducted with the following steps (Steps 4–5 are optional):

1. Construct hierarchy. Prioritization items need to be divided into one high and several low level item groups. Each low level item group is child to exactly one high level item. And each high level item has one low level item group. One low level item may belong to several item groups. Even if parts of the items are not logically connected they can be grouped separately and assigned a fake parent item, e.g. ‘misc. items’. HCV does not, as far as we know, provide any instructions for creating a requirements hierarchy.
2. Each high and low level item group is prioritized separately using CV. The stakeholder may prioritize all item groups at once or one by one. But it should be possible to prioritize groups in any order and repeatedly, because the stakeholder might learn more about the items while performing the prioritization.

In particular the stakeholder is likely to learn more about a high level item when prioritizing its low level item group [17]. Some stakeholders may prioritize only part of the groups and each group may be prioritized by different stakeholders.

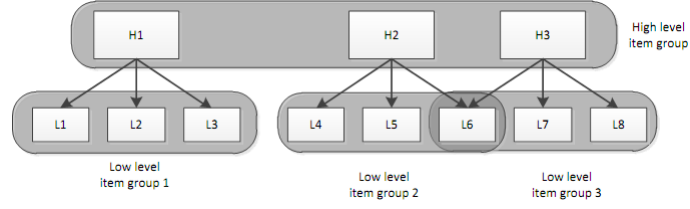


Figure 3: Overlapping prioritization item hierarchy example.

- 259 3. The priority of each low level item is normalized by dividing it with
260 the sum of all low level priorities of each item in all groups.
- 261 4. The final priority of each low level item is calculated by multiplying it
262 with the priority of its parent high level item.
- 263 5. Then one applies the compensation factor to all low level requirements
264 as described in Section 2.3.5.
- 265 6. Finally, when multiple stakeholders have performed the prioritization,
266 priorities of low level items are combined as in standard CV.

267 It is possible that one low level item is child of more than one high level
268 requirement and, thus, belongs to two or more low level requirement groups
269 (see Figure 3). Such requirements participate in the standard HCV prioritization
270 process and are prioritized two or more times with each group they
271 belong to. At the end of the prioritization they receive several priority values.
272 These values can be summed together to form the final priority of the item.
273 (This is done because the item adds value to both parts of the hierarchy.)

274 2.3.7. Example of Hierarchical Cumulative Voting

275 Suppose six requirements for a mobile phone operating system need to be
276 prioritized: ‘reminder alarm’, ‘specify repeated event’, ‘hide contact’, ‘add
277 picture to phonebook’, ‘search contact’, ‘make video call’. Three high level
278 requirements can be identified: ‘Calendar’, ‘Phonebook’, ‘Call’. The low level
279 requirements are then grouped as sub-requirements of high level requirements
280 as shown in Figure 4. The ‘Search contact’ requirement is a sub-requirement
281 and has two parent requirements: ‘Phonebook’ and ‘Call’. The computation
282 of the final priorities of requirements is shown in Table 1.

283 After requirements are grouped, and a hierarchy is defined, each group of
284 requirements are then prioritized using CV. The final priority of a low level

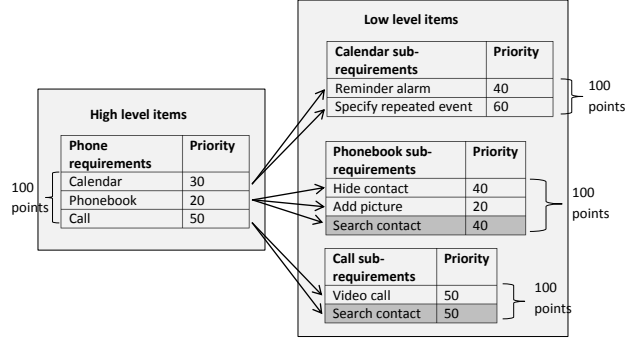


Figure 4: Example of hierarchical cumulative voting with requirement hierarchy.

Table 1: Example of hierarchical cumulative voting.

Phone requirements	Compensation factor	Sub-requirements	Priority calculation	Final priority
Calendar	2	Reminder alarm	$40 \times 30 \times 2$	2400
Calendar	2	Specify repeated event	$60 \times 30 \times 2$	3600
Phonebook	3	Hide contact	$40 \times 20 \times 3$	1600
Phonebook	3	Add picture	$20 \times 20 \times 3$	800
Phonebook & Call	3 & 2	Search contact	$40 \times 20 \times 3 + 50 \times 50 \times 2$	7400
Call	2	Video call	$50 \times 50 \times 2$	2500

285 requirement is computed by multiplying the priority of the requirement with
 286 the priority of its parent high level requirement and the compensation factor.
 287 The compensation factor in this particular case is the number of elements in
 288 a group, two for the ‘calendar’ and ‘call’ sub-requirements and three for the
 289 ‘phonebook’ sub-requirement.

290 2.4. Compositional Data Analysis

291 CV results can be seen as a special type of data, i.e. compositional data.
 292 Compositional data does not contain absolute values. It shows only the
 293 relative weight of a component compared to the whole. In [10] the authors
 294 propose the use of compositional data analysis for the statistical analysis of
 295 CV.

296 A compositional data item is a vector (x) of positive components with a
 297 constant sum k :

$$x = (X_1; X_2; \dots; X_n) \text{ where } x_i \geq 0 \text{ and } \sum_{j=1}^n x_j = k. \quad (1)$$

298 The property of the sum of the items being restricted is called the constant
 299 sum constraint. In CV, priorities assigned by a stakeholder to the items of
 300 a prioritization set is a compositional data vector with a constant sum of
 301 100. The value of k (i.e. 100 in this case) is arbitrary and does not affect
 302 the analysis of the data because the information is contained in the ratios
 303 between the components of the vector. The vector can sum up to any number
 304 but still hold the same data, i.e. vectors (1, 2, 7) and (10, 20, 70) are in this
 305 case considered equivalent. This principle is called *scale invariance*.

306 Another property of compositional data items is *subcompositional coher-*
 307 *ence*. Consider that two compositions are analysed. One composition is a
 308 subcomposition of the other. *Subcompositional coherence* means that the re-
 309 sults of the analysis are the same for the common parts of the compositions
 310 [19]. This property is important for the analysis of HCV results. Statements
 311 that are made regarding each smaller group of prioritization items are also
 312 true for all items prioritized with HCV.

313 The priority of an item is relative to the priority of the other items in
 314 the set. Hence, the priority of an individual item is meaningless without
 315 context, i.e. the complete set of items. The same item may receive different
 316 priority when put in two different prioritization sets. If the item is put in a
 317 set of items with high priority it will receive a lower relative priority. This
 318 also holds true the other way around i.e. if the item is put in a set with low
 319 priority items its priority will be higher.

320 When doing analysis of compositional data one must take into account
 321 that compositional is a special type of data and should be analysed differently
 322 than other data types. Ordinary unconstrained variables are free to take any
 323 positive or negative values, whereas, compositional data values can only be
 324 positive and have a constrained maximum value. Moreover, components of
 325 compositional data vectors are not independent from each other. The fact
 326 that an item is assigned 70 priority points means that the next item can take
 327 only values between 0 and 30. Hence, there is a negative correlation between
 328 the items.

329 Standard parametric statistical tests require that data vectors have mul-
 330 tivariate normal distribution. Vector $X = (X_1, X_2, \dots, X_n)$ is considered to
 331 have multivariate normal distribution if any linear combination of its parts

332 is normally distributed, and linear combination is defined by:

$$Y = a_1X_1 + a_2X_2 + \dots + a_nX_n, \quad (2)$$

333 where Y is the product of lineal combination and a_i is any real number.
 334 Now, since the sum of priorities assigned in CV must add up to 100, or any
 335 other constant number, at least one linear combination of X is not normally
 336 distributed because it always adds up to 100:

$$Y = 1 \cdot X_1 + 1 \cdot X_2 + \dots + 1 \cdot X_n = 100. \quad (3)$$

337 In our opinion, the above indicates, quite strongly, that CV results do
 338 not follow a multivariate normal distribution and, hence, it follows that they
 339 should be analyzed using non-parametric statistical tests [20].

340 2.4.1. Problem of Zeroes

341 Compositional data analysis requires that log-ratios between any compo-
 342 nents in a vector can be computed. But computing a log-ratio with a zero
 343 value is, in this case, meaningless. This is a problem since CV allows stake-
 344 holders to assign zero priorities to some prioritization items (we would even
 345 strongly argue that this is very common).

346 In compositional data there are two types of zeroes: essential and rounded.
 347 Essential zeroes mean that a data component is not present. Rounded zeroes
 348 mean that the component is present but its value is very low. We, as others
 349 have before us, conjecture that zeroes in CV results are rounded because the
 350 priority of an item is a completely abstract notion and the instrument for
 351 measuring priority is human judgement [10].

352 Before compositional data analysis can be applied to CV results, we
 353 should first remove zeroes in the data. One approach can be to forbid stake-
 354 holders to assign zero priorities. This approach is used in e.g. [7]. But this
 355 can add some unnecessary complexity to the prioritization process and, ex-
 356 plicitly, delimits an expert's freedom. In [10] the authors propose the use
 357 of a multiplicative replacement strategy (as defined in [21]) for CV result
 358 analysis.

This method replaces rounded zeroes with small values using the expres-
 sion

$$r_j = \begin{cases} \delta_j, & \text{if } x_j = 0, \\ (1 - \frac{\sum_{k|x_k=0} \delta_k}{c})x_j, & \text{if } x_j > 0, \end{cases} \quad (4)$$

where δ_j is the imputed value and c is the constant sum constraint. In order for the total sum of components to stay constant, the equation subtracts some value from the items with a priority higher than zero. More is subtracted from components with higher values than from components with lower values (and the value of the imputed δ_j is arbitrary).

2.4.2. Isometric log-ratio transformation

In order to apply standard statistical methods to compositional data it should be transformed to remove the inherent correlation of the values. Compositional data analysis proposes special transformations that change the compositional data values to unconstrained real values. One such transformation is isometric log-ratio (*ilr*) transformation (as proposed by [20, 22]).

After compositional data vectors are transformed using zero replacement and *ilr*, any standard statistical tests can be applied.

3. Related Work

In the previous sections we introduced requirements prioritization methods, some examples of CV result analysis methods and a more detailed description of compositional data analysis and CV.

In this section we only present systematic literature reviews performed in this field and how they relate to our study.

A systematic review of requirements prioritization methods is presented in [33]. The study focuses on prioritization method comparison and selects eight relevant studies. Two of the studies use CV. These two studies are also included in the systematic literature review conducted as part of this study. In [33] the author concludes that there is little research on requirements prioritization and studies usually deal with a small number of requirements.

In the next section we will cover the methodology of this study. As will be presented later, the systematic literature review had two purposes: to assemble data that have been used in CV and to investigate if there existed a method of analysis that would identify prioritization items with equal priority.

4. Methodology

This section covers the research questions of this study and the methods used to answer them.

392 4.1. Selection of Research Methods

393 The main purpose of this study is to collect knowledge on the use of CV
394 in order to help software engineers and researchers in adopting it.

395 One way of collecting this knowledge is to conduct an empirical study. A
396 survey in a large number of software companies can be used to quantify the
397 level of adoption of CV in industry (similarly to the study by [34]), while a
398 case study can be used to receive qualitative feedback on the use of CV [35].

399 Knowledge on the empirical use of CV can also be obtained from existing
400 studies. This may be done by means of a systematic literature review. Several
401 studies have used CV in industry as well as in academic settings. Neverthe-
402 less, there are no studies that provide an overview of the current state of the
403 practice in this field (as reported by research studies). Therefore, before con-
404 tinuing with the refinement of CV and conducting new empirical studies (i.e.
405 case study or experiment), a systematic literature review would be required.

406 This paper proposes a new method for CV result analysis, called Equality
407 of Cumulative Votes (ECV). (ECV groups prioritization items into groups of
408 items with similar priority.) As will be presented later, the systematic review
409 did not reveal any methods that solve this problem; however, ECV needs to
410 be evaluated and, hence, applied to CV results.

411 There are two options to obtain CV results in order to test ECV. One is
412 to conduct a new empirical study. The second option is to collect CV results
413 from existing studies. The latter approach also has the added benefit of
414 trying to replicate the results from previous studies and, if data from several
415 other studies are used, a larger amount of data can be obtained. Moreover,
416 the generalizability of the evaluation increases when prioritization results
417 from different sources and domains are used. On the other hand, the main
418 benefit of conducting a separate empirical study is the possibility to control
419 the conditions of CV.

420 In our study we evaluated ECV by obtaining data from previously con-
421 ducted studies as found by the systematic literature review. In order to
422 obtain the data, authors of relevant primary studies were contacted.

423 In short, this study consists of two parts: a systematic literature review
424 (SLR) of CV and an evaluation of ECV based on the data from the primary
425 studies found in the SLR.

426 4.2. Research Questions

427 The systematic review should focus on catching studies that empirically
428 use CV. Information about place, time, scale, and domain of the studies

429 should be collected and the results of the review will hopefully aid academic
430 researchers by identifying paths for further investigation of CV. Hence, the
431 first research question is:

432 **RQ 1.** What is the state of practice in empirical studies that use CV?

433 The level of trust in research results considering CV is determined by the
434 quality of the studies that use CV, hence this study includes an evaluation
435 of the quality of primary studies identified by the systematic review.

436 Next, a valuable aspect of decision-making is the analysis of prioritization
437 results. Thus, the second research question is:

438 **RQ 2.** What CV result analysis methods have been presented in papers as
439 identified by RQ 1?

440 Finally, the evaluation of ECV answers the third research question:

441 **RQ 3.** Is ECV capable of identifying prioritization items with equal priority?

442 **5. Systematic Literature Review**

443 This section presents the design of the systematic literature review. For
444 the results of the execution please see Section 7.1 and 7.2.

445 Table 2 presents an overview of activities performed during the systematic
446 literature review. The review protocol was developed by one researcher and
447 evaluated by another researcher. Studies were searched for in two iterations.
448 The first search was performed using databases. The second search was
449 performed using snowball sampling [36] (snowball sampling examines the
450 references of primary studies revealed by the first search). References that
451 are relevant to the review, i.e. they pass the selection criteria, are then added
452 to the set of primary studies.

453 The search for papers was performed by a single researcher. Study se-
454 lection, on the other hand, was performed by two researchers. First, one
455 researcher examined all found studies. Next, another researcher re-examined
456 all studies classified as primary studies in addition to 20 randomly selected
457 excluded studies to ensure the quality of the selection.

458 To ensure the quality of the review, the quality evaluation and data ex-
459 traction was performed independently by two researchers. Inter-rater analy-
460 sis was performed using Krippendorff’s Alpha statistics [37, 38].

Table 2: Review activities.

Review phase		Researchers involved
Trial search in databases		A
Develop review protocol		A
Evaluate review protocol		B
Paper search and selection from databases	Search in databases	A
	Search string validation	A
	Selection based on metadata	A and B
	Selection based on full text	A and B
Pilot data extraction (3 papers)		A
Paper selection from the reference lists	Selection based on metadata	A and B
	Selection based on full text	A and B
Data extraction		A and B
Data synthesis		A

461 5.1. Data Sources and Search Strategy

462 The SLR was designed based on the guidelines by Kitchenham [39]. First
 463 a trial search in electronic databases was conducted. In order to scale the
 464 review to a manageable, yet sufficient size, databases were searched with dif-
 465 ferent search strings. Relevant papers that were found during the trial search
 466 were used to extract additional search strings. The trial search revealed that
 467 the number of studies that use CV is not very large. Therefore, we decided
 468 to include not only software engineering studies but also studies in other re-
 469 search areas, such as forestry or corporate governance, since one key aspect
 470 we intended to investigate was analysis methods for CV.

471 Since CV is frequently used in studies without mentioning this in the
 472 abstract, full text search in databases is preferable. Unfortunately not all
 473 databases support full text search. Full text search was performed in the
 474 IEEE Xplore and Springer Link databases. In ACM Digital Library, In-
 475 spec/Compendex, ISI Web of Knowledge, and SCOPUS only metadata was
 476 searched. The search strings used, consisting of a Boolean expression (A or
 477 B or C or D or E or F or G), where:

- | | |
|---------------------------|-------------------------------|
| 478 (A) Cumulative voting | 482 (E) hundred dollar method |
| 479 (B) 100 dollar method | 483 (F) hundred dollar test |
| 480 (C) 100 dollar test | |
| 481 (D) 100 point method | 484 (G) hundred point method |

485 Search strings contained only synonyms of CV and they did not limit the
 486 research area to software engineering. The search was performed indepen-
 487 dently using each of the search strings in each database. All search results
 488 were combined and documented using reference management software. The
 489 quality of the search strings and the selection of electronic databases were
 490 validated against a previously known core set of papers—[3, 10, 28, 40]—
 491 checking that all papers from the core set were found by the search.

492 5.2. Study Selection

493 To select relevant papers a set of criteria were designed. The criteria for
 494 paper selection are presented in Tables 3 and 4.

495 Papers were selected in two phases: based on metadata and based on full
 496 text.

Table 3: Paper search and selection in the databases.

Selection phase	Inclusion criteria	Number of papers selected
Search in databases	published 2001–2011 (databases last accessed Feb. 20, 2011)	256
	contains search strings	
Selection based on metadata	exclude duplicates and tables of contents	177
	written in English	
Selection based on full text	full text is available	127
	study involves empirical use of CV or presents analysis of empirical use of CV	58
	CV is done by humans and not software	25

Table 4: Paper selection from the reference lists of the selected papers.

Selection phase	Inclusion criteria	Number of papers selected
Selection from references	papers included in the reference lists of relevant papers found in databases	467
Selection based on metadata	written in English	462
	reference is already revealed by search in databases	450
Selection based on full text	full text is available	329
	study involves empirical use of CV or presents analysis of empirical use of CV	15
	CV is done by humans and not software	

Obviously, the main criterion for inclusion of a paper is that it must present empirical use of CV or present an analysis of the results of using CV. However, there are papers that pass this criterion but are not relevant for this review. CV is frequently used in computer algorithms. There is a significant difference between the way humans and computers make decisions. Since this review is concerned with human decisions we excluded papers that present CV that is not performed by humans. In addition, only papers that were written in English were selected and duplicate studies were automatically excluded by the citation management software used in this review. We searched for papers between 2001–2011. By then performing a snowball sampling of these papers we are convinced that we have a representative sample and, furthermore, that the bulk of the studies are relevant from a software engineering perspective.

510 5.3. *Quality Evaluation*

511 The goal of quality evaluation is to determine the best primary studies
512 according to some measure of quality. Since the number of studies that use
513 CV is not large, quality evaluation was not used as an exclusion criterion.

514 The quality of a study obviously depends on the correctness of the study
515 process including planning, operation, analysis and interpretation of the re-
516 sults (is the study right?) The correctness of the process can be measured
517 by evaluating the description of the study or replicating the study. Thus,
518 to gain the trust of industry practitioners and other researchers, the process
519 of the study should be rigorously described. In short, the description has to
520 facilitate the replication of the study as well as the presentation of limitations
521 and validity threats.

522 Even the most correct and rigorously described study is useless if it does
523 not contribute to the industry or research community (is it the right study?)
524 The topic of the research ought to address important goals and issues. The
525 findings of the study should also be significant, i.e. there is a high probability
526 of the results of the study are true. The significance of the findings depends
527 on how realistic the study is, the correctness of the process and the results
528 of the study, as well as the statistical significance of the findings.

529 **Realism** of a study depends on the context, scale, and subjects of the
530 study. The study should be conducted in a **setting** that is similar or equal
531 to the setting in which the findings of the study are intended to be used.
532 Hence, studies that are conducted in an industrial setting are in many cases
533 valuable. The **subjects** of a study should be similar to the people who are
534 supposed to use the findings of the study. The subjects ought to have appro-
535 priate work experience, role in the organization, skills, cultural background,
536 motivation, and so forth. The **scale** of a study refers to the size of the study
537 objects. In the case of this systematic review the scale of a study is mea-
538 sured as the number of prioritization items. Study in academia may have a
539 large number of prioritization items. At the same time, an industrial study,
540 with professionals as subjects, may involve a smaller number of prioritization
541 items.

542 Each study may have a different level of realism. Some studies involve
543 industry practitioners in an academic setting to simulate real word practice in
544 a laboratory environment. Other studies may involve academic researchers
545 that execute a project. For example, researchers may be developing open
546 source software. On the reality scale these studies are somewhere in between
547 the purely academic and industrial studies.

548 The **type** of the research study can be considered as a criterion for the
549 evaluation of study realism. Reference [41] suggest that study designs that
550 are more rigorous (e.g. experiments) are more realistic than observational
551 studies (e.g. case study) due to a higher level of control. On the other hand
552 [42] rate study designs based on other criteria, i.e. how frequently each type
553 of study design is used in an industrial or academic setting. If a study design
554 is used more in an industrial setting, then it is considered more realistic.
555 For instance, in software engineering, case studies are frequently used in
556 industrial settings, whereas, experiments are usually performed in academia
557 using students as subjects. Therefore, [42] argue that case studies are more
558 realistic than formal experiments. Obviously the effect of study design on
559 the study realism may be interpreted in different ways. Therefore, we will
560 not use this parameter in our quality evaluation.

561 The statistical significance of the results of a study can be used to evaluate
562 the significance of the study findings. This measure will not be used, because
563 the studies that are evaluated belong to very different research areas, i.e. the
564 significance levels of the findings of the studies are not directly comparable
565 for meta-analysis. Additionally, sometimes no result is more interesting than
566 a significant result, i.e. it may reveal important gaps in existing knowledge.

567 The ultimate goal of research, at least in software engineering, is in many
568 cases industry impact. However, most of the time ideas need to be devel-
569 oped and validated in academia before industry professionals will risk to
570 adopt them. Therefore, academic impact is important as well. Academic
571 impact is usually measured by the number of citations. Academic impact is
572 also measured for particular researchers, using the number of papers she has
573 published and the number of times her papers have been cited. This measure
574 will not be used in our quality evaluation because it is somewhat biased. The
575 number of citations is likely to be lower for newer papers and the number
576 of papers that a researcher has published gives little information about the
577 actual quality or impact of her research.

578 5.3.1. *Rating of the Studies*

579 The quality evaluation in our review is based on the evaluation of: (i)
580 Study realism. (ii) Study scale. (iii) Availability of raw results of CV. (iv)
581 Quality of the research methodology.

582 Realism of the studies is rated in three aspects: subjects, setting, and
583 scale. The subjects and setting is rated according to Table 5. The total
584 rating of study realism is determined by summing up the ratings of the two

Table 5: Rating of study reality level.

Aspect	Contribute to relevance (rating 1)	Do not contribute to relevance (rating 0)
Subjects	Industry professionals	Academia students or teachers, or other
Context	Industrial	Academia

585 aspects. For instance, if a study is conducted with industry professionals
 586 as subjects in an academic context the study will receive rating 1 (out of 2
 587 maximal points).

588 In order to rate the scale of a study the number of prioritization items was
 589 counted. If a paper presents several prioritization cases only the prioritization
 590 with the largest number of the prioritization items is considered. If HCV is
 591 used all of the prioritization items on different levels are counted together.
 592 However, if an item is present in several groups in the hierarchy it is counted
 593 only once.

594 The availability of raw results from the application of CV is rated sepa-
 595 rately because it is especially important for our purposes (and for most other
 596 researchers in order to replicate a study). The data availability rating criteria
 597 is given in Table 6. If the data of a study is not available it is not possible
 598 to validate the results of the study and, hence, the credibility of the findings
 599 is lower. Ideally the data collected in the study should be presented directly
 600 in the paper. An alternative may be to make the data freely available online
 601 and reference the online source.

602 The quality of the research methodology of a paper is rated according to
 603 a checklist presented in Appendix C. The checklist is based on guidelines
 604 for presenting research studies (as presented in [43, 44]) and the guidelines
 605 for quality evaluation of research studies as presented in [39, 42]. Evaluation
 606 is done with regard to the rigor of the description and correctness of the
 607 research process and reasoning. Checklist items represent issues that research
 608 studies should implement and present in a research paper. The checklist also
 609 contains item descriptions or questions that are used to evaluate the quality.
 610 Each item in the checklist is rated according to criteria presented in Table 7.
 611 The final rating of correctness of the research process of a study is computed
 612 by summing up the ratings assigned to all items in the checklist.

613 Study rating criteria was validated during a trial data extraction. Two
 614 researchers each rated three randomly selected papers. Afterwards, differ-
 615 ences in ratings were discussed and study rating criteria were updated to
 616 avoid differences in interpretation.

Table 6: Research data availability rating.

Rating	Study rating criteria
0	CV results was not provided in the paper and we was unable to obtain the results from the authors.
1	CV results are not provided in the paper but the data was obtained from the authors. Part of the data is lost or corrupted.
2	CV results are not provided in the paper but all the data was obtained from the authors.
3	All CV results are included in the paper or reference is given to online source where all the data can be accessed.

Table 7: Rating of correctness of research process.

Rating	Study rating criteria
0	No description provided.
1	Only basic information is provided about the checklist item. Or significant validity threats exist with regard to this item.
2	Description is sufficient. Some minor questions are left unanswered. Validity threats may exist but they are not likely to affect the results of the study.
3	Description is rigorous and clear. Questions presented in quality evaluation checklist in Appendix C are answered. Decisions of the study are well justified, alternatives are discussed. No unhandled validity threats can be identified.

As a result of the rating each study was assigned four rating values on an ordinal scale. In order to perform a more advanced analysis of the quality evaluation results these ratings were then converted into ratio scale ranks. For each study, the number of studies that had received lower ratings were counted. The resulting number is the rank of the study; thereby, the quality of a study is expressed as four rank values.

An example of rating values is shown in Table 8. Table 9 shows ranking values computed for the studies in Table 8. We can observe that study realism level rating for ST3 is 0. There are no studies that have a lower study realism. Therefore, realism ranking for ST3 is 0. ST1 on the other hand has the highest realism rating. Since ST1 has higher reality level than both ST2 and ST3 it is assigned reality level rank 2.

Table 8: Example of rating values.

Study	Realism	Research data availability	Correctness of research process	Number of prioritization items
ST1	2	0	15	6
ST2	1	3	20	69
ST3	0	3	10	6

Table 9: Example of ranking values.

Study	Reality level	Research data availability	Correctness of research process	Number of prioritization items
ST1	2	0	1	0
ST2	1	1	2	2
ST3	0	1	0	0

5.4. Data Extraction

The goal of data extraction is to understand how and why CV is used and how CV results are analysed in research studies. Ultimately, this will allow us to answer the first and second research questions in our study.

Data extraction was documented with the help of spreadsheet software. Extracted data items are available from [45].

6. Equality of Cumulative Votes

In the previous section we described the execution of the systematic literature review. In order to perform a more thorough analysis later we here present the design of ECV before presenting the results of the systematic literature review. For the results of the evaluation of ECV please see Section 7.3 (ECV is implemented in the *R* programming language [46] and the code can be found at [47].)

In CV stakeholders may assign similar or equal values to several prioritization items. As a result the difference between the items is small. The variation in priorities is caused not only by the difference between prioritization items but also by human error and lack of information. For instance, people tend to simplify the task of prioritization by assigning rounded values to items or giving equal values to several items [48].

During prioritization it may be beneficial to know which items are equal. A common example is software release planning where requirements are distributed among several product releases. If two or more requirements are considered equal they can be interchanged between the releases regardless of their priority. That allows other criteria, such as cost or effort, to be used as sole indicators for planning that particular release.

6.1. Testing Equality of Two Items

There are two ways to determine which prioritization items have similar priority. One approach is to find items that are different and consider other

657 items as equal. Another approach is to find items that are equal.

658 The first approach uses statistical tests to evaluate differences between
659 e.g. two sample means, in order to determine that two items are different.
660 Samples in this case consist of priorities assigned by all stakeholders to a
661 particular prioritization item. The number of stakeholders that perform the
662 prioritization is frequently small. Hence, the size of the sample is very often
663 too small for statistical tests to detect a significant difference in the tests,
664 thus, identify too many equal items to make any useful conclusions.

665 ECV, in contrast, uses the second approach. It finds items that are
666 similar and the rest of the items are considered different. This method tests
667 the probability of the difference between the means of two items being smaller
668 than the given value. In short, ECV tests the probability of the means of two
669 prioritization items differing by less than 25%. If the probability is higher
670 than 70% the items are considered equal.

671 The input to ECV is an $n \times p$ matrix A that contains the raw results of
672 the prioritization. The columns of the matrix represent prioritization items
673 while rows represent stakeholders. ECV performs the following operations
674 for the priorities of each of the two prioritization items:

- 675 1. Replace zeroes in CV results.
- 676 2. Transform the data using *ilr* transformation.
- 677 3. Determine distribution function using kernel density estimation.
- 678 4. Use the distribution function to find the probability that the difference
679 between two prioritization items is smaller than 25%.
- 680 5. Form groups of equal prioritization items.

681 Since CV results are compositional data, zeroes in A are replaced with
682 other values. This is done using the multiplicative replacement strategy
683 which is described in Section 2.4.1. Next, two columns are extracted from
684 matrix A to create the new matrix B :

$$B = [a_{*,k} a_{*,l}], \quad (5)$$

685 where a is an element of matrix A , and k and l are the columns that repre-
686 sent items that are tested for equality, " $*$ " denotes all rows of corresponding
687 column.

688 The *ilr* transformation is then applied to each row of the matrix B and
689 the new vector C is obtained. The equation for calculating elements of C
690 using *ilr* transformation is:

$$c_i = ilr(b_{i1}, b_{i2}) = \sqrt{0.5} \log(b_{i1}/b_{i2}), \quad (6)$$

691 where c_i is the i^{th} element of C and b_{i1} and b_{i2} are the first and second
692 elements in the i^{th} row of B . Each value c_i represents a log-ratio between
693 values of columns k and l . The mean of the values of C can be interpreted as
694 an average log-ratio between the items that expresses the difference between
695 the items.

696 After the data is transformed into log-ratios statistical test can be applied.
697 The purpose of the test is to determine what the probability is of the relative
698 difference between two prioritization items k and l being less than 25%. Or
699 in terms of log-ratios it means determining the probability of c_i (obtained
700 from priorities assigned to k and l) as being in the range of $\frac{3}{4}$ to $\frac{4}{3}$. Hence,
701 the objective of the test is to determine the probability of the sample mean
702 (i.e. mean value of the items of C) laying between the two values.

703 The probability that the mean takes a particular value can be expressed
704 in the form of a cumulative distribution function. The probability of the
705 mean being between two values a and b (where a is smaller than b) can be
706 determined by subtracting the probability of the mean being smaller than a
707 from probability of the mean being smaller than b .

708 However, CV result data may or may not have multivariate normal dis-
709 tribution. If the data is normally distributed a Student's t -test can be used;
710 otherwise, a non-parametric estimation of the distribution function is needed.

711 Otherwise a non-parametric estimation of the distribution function could
712 be performed. In our case, the CV result data obtained from the primary
713 studies identified by the systematic review, were tested for normality using
714 the Anderson-Darling test. Before applying the test the data was transformed
715 using methods of compositional data analysis. To compute the test we used
716 method *adtestWrapper* from R language library *robCompositions*.

717 The tests we performed indicated, quite strongly, that in most of the
718 prioritization cases the data is not normally distributed. Hence, our rec-
719 ommendation is that, in general, a non-parametric approach should be used
720 to determine the probability density function, and one such, common, ap-
721 proach would be to use the kernel density estimation. (In our implementation
722 of ECV in the R programming language, kernel density estimation is per-

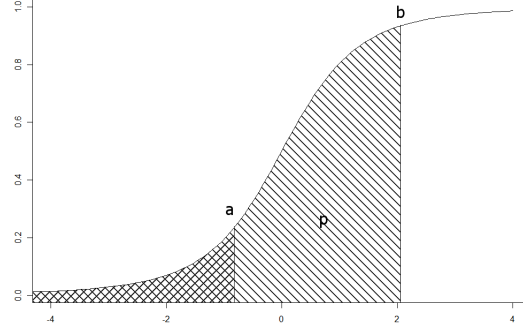


Figure 5: Cumulative distribution function of the log-ratio c_i between the items k and l (area p denotes probability that c_i is between $\frac{3}{4}$ and $\frac{4}{3}$.)

Table 10: Example of an equality table.

prioritization items	i1	i2	i3	i4
i1	equal	equal	-	equal
i2	equal	equal	-	-
i3	-	-	equal	-
i4	equal	-	-	equal

723 formed using the package *ks*.)

724 To determine the probability of \bar{x} being between a and b the following
725 equation is used:

$$p = P(b) - P(a), \quad (7)$$

726 where P is the cumulative distribution function obtained by applying
727 kernel density estimation on *ilr*-transformed priority values denoted by vector
728 C . Variable a is equal to $ilr(3, 4)$ and b is equal to $ilr(4, 3)$. (A graphical
729 interpretation of Equation (7) is presented in Figure 5.) The area that is
730 denoted by letter p represents the probability computed by the equation.

731 After both prioritization items are tested for equality it may be convenient
732 to display the equality of different items in the form of a table. Please see
733 Table 10 for an example.

734 6.2. Grouping Prioritization Items

735 When equal items are determined they can be divided into groups of equal
736 items. Division is performed in such a way that each two items in a group
737 are equal. The test for equality of the items described in Section 6.1 is not
738 transitive. Hence, if prioritization item A is equal to B and B is equal to C

739 then it does not automatically imply that A is equal to C . Therefore, there
740 may be several ways to group the equal items. The two possible division
741 criteria that we have considered in this study are:

- 742 1. Maximize the number of items that have a group.
- 743 2. Maximize the number of items in each group.

744 Current implementation of ECV (available from [47]) does not include
745 the division of items into groups. In this study the division is done manually,
746 so that each two items in a group are equal.

747 7. Results

748 This section presents the results of this study including the systematic
749 literature review and the application of ECV on industry and academic data
750 collected from the primary studies. Data extracted from primary studies and
751 the results of the quality evaluation are available in [45].

752 7.1. *State of Practice in Empirical Studies that use CV or Analyze the Re-* 753 *sults of CV (RQ 1)*

754 The study search resulted in 634 unique studies. The search in databases
755 revealed 180 papers, while an additional 454 papers were discovered us-
756 ing snowball sampling. The study selection resulted in 40 primary studies.
757 Hence, 94% of the studies were excluded by the selection criteria. Snowball
758 sampling revealed 15 (36%) out of all primary studies. The study selection
759 criteria and the number of papers excluded by each criterion are shown in
760 Tables 3 and 4. In total 163 of 634 studies were excluded because full text
761 was not available.

762 All results of the study selection are available online and can be obtained
763 by contacting the authors of this paper. For each study we specify keywords
764 and databases that were used to find the study. If a study has been excluded,
765 the exclusion criteria are provided.

766 The number of papers revealed by each search string and database is
767 presented in Table 11. It should be noted that several papers were found by
768 more than one search string or in more than one database. Table 11 shows
769 that the search string ‘cumulative voting’ was the most frequently used in
770 the research community to denote CV. Therefore, researchers should use or
771 reference this term when discussing CV.

To perform snowball sampling we examined the references of primary studies that were found during the database search. References were used to search for the papers in the Google and Google Scholar search engines. Studies that were found in the search and passed the study selection criteria were added to the set of primary studies.

After the primary studies were selected, data extraction and quality evaluation was performed by two researchers. One researcher examined all studies while the second researcher did quality evaluation and data extraction for 10% of the studies. The studies were randomly selected. Inter-rater agreement were calculated by means of Krippendorff's alpha coefficient. Agreement for data extraction results was 0.86 and agreement for the quality evaluation was 0.73. According to [38] it is common to require agreement above 0.8 and the lowest acceptable agreement is 0.667. Therefore, we conclude that the agreement calculated for this study is sufficient. Ratings of the study setting, correctness, research data availability, and number of prioritization items are presented in Figure 6.

Table 12 shows the studies with the highest quality according to our criteria. These studies show a high level of rigor in a realistic setting. Moreover, authors of the studies manifest confidence by providing raw data for further use and evaluation.

Figure 7 shows a bubble chart of the distribution of studies over research areas and time. The figure shows that CV was, as far as we know, first applied some time ago in research of government elections. Nowadays, though, CV has been adopted in a wide range of software engineering areas, most frequently in requirements engineering and software release planning. Eight studies use CV in academia while the remaining 32 studies report on using CV in industry.

7.2. CV Result Analysis Methods Identified by RQ 1 (RQ 2)

The papers identified in the review use various CV result analysis methods. The main goals for CV result analysis are presented in Table 13 and a summary of methods used in the primary studies can be found in Section Appendix B.

In order to present prioritization results many studies use charts or tables. These charts and tables show the average priority of each prioritization item that is computed from priorities assigned by all stakeholders. In [54] a table of five items with highest total priority is presented. [55] shows tables with min , max , \tilde{x} , \bar{x} and σ of priorities assigned by different stakeholders to a

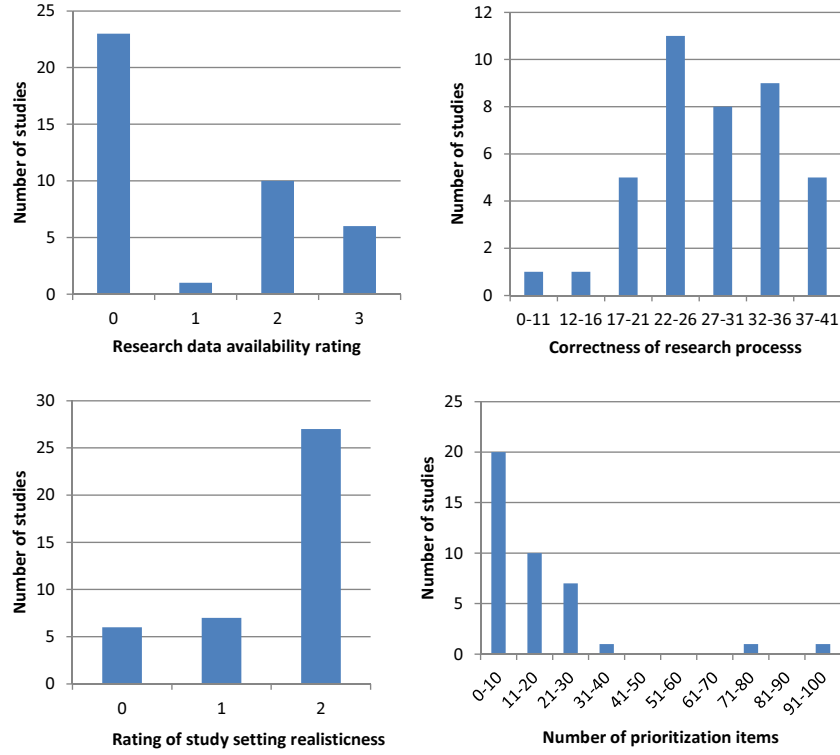
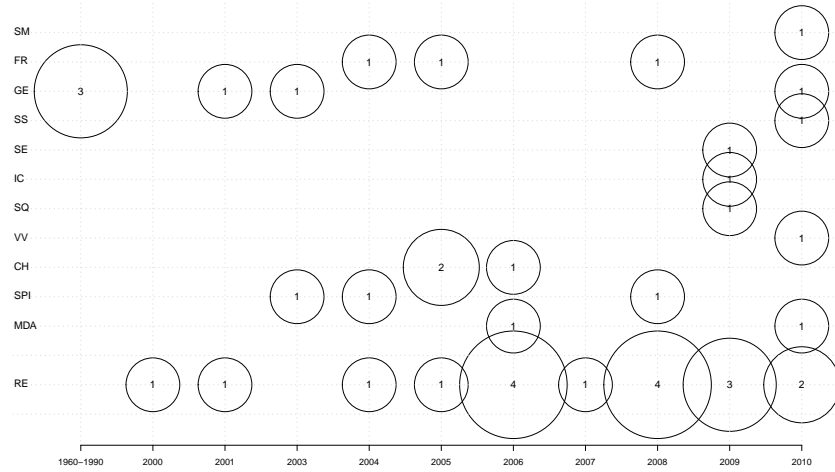


Figure 6: Study quality ratings.

Table 11: Number of papers found in the databases.

database	search strings							unique papers found	primary studies selected
	"100 point method"	"100 dollar method"	"100 dollar test"	"hundred point method"	"hundred dollar method"	"hundred dollar test"	"cumulative voting"		
ACM	2	0	0	1	2	3	31	34	7
IEEE	3	2	0	1	2	6	38	46	11
Inspec/Compendex	1	0	0	1	1	1	22	14	7
ISI web of science	0	0	0	0	1	1	15	16	6
SCOPUS	2	0	0	0	1	2	24	25	9
Springer	2	0	2	0	2	2	89	95	6
unique papers found	6	2	2	1	4	11	165	180	
primary studies selected	1	2	1	1	2	4	18		25



MDA - model driven software development
 CH - change impact analysis in software engineering
 RE - requirements engineering and software release planning
 IC - intellectual capital in software company
 SPI - software process improvement
 V&V - software verification and validation
 FR - forestry
 GE - government elections
 SS - software security
 SQ - software quality
 SM - software metrics
 SE - software engineering in general

Figure 7: Distribution of studies over time.

Table 12: Top ranked studies.

	Correctness of research process	Research data availability	Study setting	Number of prioritization items
Barney 2009 [49]	36	2	2	17
Berander 2009 [17]	41	2	0	29
Barney 2009 [50]	40	2	2	5
Barney 2009 [8]	31	2	2	27
Barney 2008 [51]	34	2	2	14
Laukkanen 2005 [52]	22	3	2	30
Hu 2006 [53]	34	2	1	14
Feldt 2010 [29]	24	3	2	8
Regnell 2001 [40]	21	3	2	91
Svahnberg 2008 [30]	34	1	1	7

809 particular prioritization item. Finally, in [55, 56] error bars are added to the
810 chart of final priorities (denoting σ of priorities).

811 In a few cases final priorities are presented in the form of ranks and
812 CV results are degraded from ratio to ordinal scale. This is done when the
813 interest lies only in the order of final priorities.

814 Several papers are interested in the difference between priorities from dif-
815 ferent prioritization perspectives (e.g. current and ideal situation) or stake-
816 holder groups (e.g. software developers and management). Pearson or Spear-
817 man correlation coefficients are commonly used to determine what the level of
818 similarity is between all priorities from two perspectives. Whereas, Wilcoxon,
819 Kruskal-Wallis, Nemenyi-Damico-Wolfe-Dunn tests and the χ^2 statistic are
820 used to detect if there is a significant difference in the value of one prioritiza-
821 tion item from two or more perspectives. In addition, PCA is used to detect
822 if there are distinct groups of stakeholders with common priorities [7, 10, 57].

823 In some cases, a stakeholder may assign equal priority to several prioritiza-
824 tion items or leave several items unrated, e.g. the stakeholder may not have
825 carefully considered all prioritization items. Hence, the difference between
826 the items may have been unnoticed.

827 In [4] the scalability of prioritization is measured using two charts. The
828 first chart shows the average percentages of items given a non-zero value.
829 The second chart shows average percentages of divergence of values. If a
830 stakeholder assigns equal priorities to many prioritization items the diver-
831 gence of values is low. Unfortunately it is unclear from [4] how the average
832 percentage of divergence is calculated.

833 In [58] distribution, disagreement, and satisfaction charts are presented.
834 The distribution chart shows how the final value of a prioritization item
835 is constructed from priorities assigned by different stakeholders. This chart
836 shows how much each stakeholder has contributed to the final value of a prior-
837 itization item. The disagreement chart shows the level of agreement between
838 different stakeholders on the value of a particular prioritization item. The
839 satisfaction chart shows stakeholder satisfaction with prioritization results
840 by calculating the correlation between final priorities and priorities assigned
841 by a stakeholder.

842 The use of bi-plots and ternary plots are proposed in [10]. A bi-plot shows
843 final priorities and stakeholder viewpoints in a two dimensional plane while a
844 ternary plot shows prioritization items inside a triangle. Ternary plots show
845 how many low, medium or high priorities are assigned to a prioritization
846 item. The corners of the triangle represent high, medium, and low priority,

Table 13: Goals for CV result analysis.

Purpose of the method	Name
Show the final priority of each prioritization item. Stakeholder priorities are combined into one value.	Chart or table of final priorities
Difference between priorities assigned by different perspectives (status quo, ideal situation) or different stakeholder groups (developers, management) [10]	Bi-plot
detect stakeholder groups with similar priorities [10]	Bi-plot
show the relative number of issues that have received high, medium, or low priority [10]	Ternary plot
detect stakeholder groups with common priorities [10]	PCA
how the final value of prioritization item is constructed from priorities assigned by different stakeholder. This chart shows how much each stakeholder has contributed to the final value of prioritization item [58]	Distribution chart
the level of agreement between different stakeholders on value of particular prioritization item [58]	Disagreement chart
satisfaction of a stakeholder with the prioritization results by the calculating correlation between the final priorities and priorities assigned by a stakeholder [58]	Satisfaction chart
percentage of the divergence of the priorities assigned by a stakeholder [4]	average percentage of divergence
average percentage of items given a non-zero value [4]	
detect equal prioritization items (presented in this paper)	ECV

847 e.g. if a prioritization item has received mostly high priority values then it is
848 shown closer to the high priority corner.

849 7.2.1. Problems with Data Analysis in Primary Studies

850 A few primary studies, as revealed by the systematic review, have prob-
851 lems with the data analysis. These studies disregard the compositional nature
852 of CV results.

853 In [7, 57] standard PCA is performed without applying log-ratio trans-
854 formations to compositional data. According to [59], this is likely to be
855 inadequate and in [60], a more appropriate method for performing PCA on
856 compositional data is presented.

857 The normality of compositional data is defined in [61]. It is stated that
858 it is convenient to transform compositional data using isometric log-ratio
859 transformation before the tests for normality can be applied. [54] violates
860 this requirement by applying the Shapiro-Wilk test for normality to untrans-
861 formed compositional data.

862 The Kruskal-Wallis test is used in [54] to analyze compositional data.
863 The test is used to evaluate the difference between three organization levels.
864 The Kruskal-Wallis test assumes that variables within each sample are in-
865 dependent [62]. However, values within compositional data vectors are not

Table 14: Identified groups of equal items.

Paper identifier & Description	Type of CV	Pairs of equal items	Groups of equal items
Barney 2009 [50] Perceived priorities of software product investments in an ideal situation	comp. HCV	(A2, B4) (B4, B5) (B4, C1) (B5, B15) (B6, B7) (B7, B8) (B14, B15) (B14, B18) (B17, B18)	(A2, B4) (B4, C1) (B5, B15) (B6, B7) (B14, B15) (B17, B18)
	uncomp. HCV	(B4, B5) (B4, B8) (B5, B15) (B6, B7) (B7, B12) (B14, B15) (B14, B18) (B16, B17) (B12, B13)	(B4, B5) (B5, B15) (B6, B7) (B14, B15) (B16, B17) (B12, B13)
Berander 2009 [17] Software requirements for course management system	uncomp. & comp. HCV	(3:2, 3:3)	(3:2, 3:3)
Svahnberg 2008 [30] The view of academia researchers on the requirements understandability criteria	CV	(Development, Verification & Validation) (Development, Product Planning 1)	(Development, Product Planning 1)

866 independent (as described in Section 2.4). Hence, we claim the Kruskal-
867 Wallis test to be somewhat misused in [54].

868 7.3. Identifying Prioritization Items with Equal Priority Using ECV (RQ 3)

869

870 This section presents the results of applying ECV to the industrial and
871 academic CV data as found through the systematic literature review. Six
872 primary studies included the raw prioritization results in the paper itself or
873 referenced online sources where the data was available. To collect the data
874 from the remaining 34 papers, the authors of all papers were contacted.

875 First, the email addresses provided in the papers were used. If no answer
876 was received authors were searched for using Google, Facebook and LinkedIn.
877 Authors from 11 papers provided us with data to be used in the evaluation
878 of ECV. However, due to confidentiality reasons we can not publish this data
879 directly.

880 In short, ECV was applied to 27 CV prioritization cases from 14 studies.
881 In the cases of HCV, ECV was applied two times to the same data to test both

882 compensated and uncompensated priorities. Equal items were detected in
883 three prioritization cases. A summary of the results is presented in Table 14
884 and below follows a summary of each relevant study.

885 In [30] a prioritization of requirement understandability criteria is pre-
886 sented. One of the main findings of the paper is that two criteria - "De-
887 velopment" and "Verification & Validation" - are most important from an
888 academic viewpoint. ECV adds new knowledge to these results. It shows
889 that "Development" and "Verification & Validation" are equally important,
890 i.e. it is not true that either one of the criteria is more important.

891 A prioritization of software requirements for an academic course man-
892 agement system is presented in [17]. ECV detected that two features—
893 Assignment Submission and Assignment Feedback—have the same priority.
894 If the system is developed in several releases Assignment Submission and As-
895 signment Feedback features can be freely interchanged between the releases
896 and, hence, in this way ECV simplifies release planning.

897 In [50] software product investments are prioritized with HCV. The re-
898 sults of ECV was different for uncompensated and compensated HCV. When
899 compensated HCV was used ECV detected equal items that belonged to dif-
900 ferent high level prioritization groups (*A*, *B* and *C*) indicating that ECV
901 provided a more fine-grained view. In the case of uncompensated HCV, on
902 the other hand, all equal items belonged to one high level prioritization group
903 (group *B*).

904 8. Discussion and Conclusions

905 This section discusses the results of the systematic review and evaluation
906 of ECV conducted as part of this study.

907 CV has been applied in various areas, but most frequently in requirements
908 prioritization and release planning, and quite often also as part of research
909 methodologies. A large part of the studies have been conducted in Sweden,
910 at Ericsson AB. One can see a slight increase in the interest in CV. During
911 the last five years there have been more studies that use CV than between,
912 say, 2000–2005.

913 Overall, studies that use CV or analyze the results of CV have a high
914 quality in terms of correctness of research process and study realism. How-
915 ever, very few studies present prioritization of more than 30 items and the
916 availability of research data is somewhat limited. In our particular case we
917 were able to obtain data from 43% of the primary studies.

918 *8.1. Implications for Practitioners*

919 The results of this study provide decision support for industry practition-
920 ers. We believe that a collection of state of the practice studies help the
921 adoption of CV prioritization method. (The top studies are summarized in
922 Table 12.) In addition, a set of CV analysis methods enables comprehen-
923 sive understanding of the prioritization results. (The analysis methods are
924 presented in Table 13.) One of the most common goals of CV analysis is to
925 display the prioritization results and, thus, to show the difference between
926 several prioritization perspectives.

927 Additionally, we present ECV—a novel method for CV analysis. Priori-
928 tization often results in the assignment of similar priorities to several prior-
929 itization items. CV results contain both ‘real priorities’ and random errors.
930 Due to random errors, equal prioritization items may receive different pri-
931 orities. ECV identifies such items. It allows stakeholders to disregard the
932 random part of the CV results. Thus, ECV simplifies the understanding of
933 the prioritization results.

934 ECV identifies prioritization items with similar priority and tests whether
935 these items can be considered equal. In this case, ECV can be used in
936 software release planning. For example, let us suppose that a set of software
937 requirements are prioritized with regard to the implementation costs. First of
938 all, ECV can then detect items with equal cost. Second, the equal items can
939 be freely interchanged between the releases. Finally, the decision to allocate
940 a requirement to a particular release can be made based on another criteria,
941 such as risk or business value.

942 ECV has been successfully applied on a considerable amount of CV data
943 and, additionally, has also detected equal items in different groups of HCV
944 hierarchies.

945 *8.2. Implications for Academia*

946 In the systematic review 36% of papers were revealed by the snowball
947 sampling. That is a considerable amount. Several studies do not mention
948 the name of the prioritization method (i.e. cumulative voting or hundred
949 dollar test). Others are not available through selected databases because
950 they are conference publications or theses. It shows, in our opinion, that
951 snowball sampling ought to be used in all systematic literature reviews.

952 CV results are a special type of data—compositional data. Standard sta-
953 tistical analysis methods that assume the independence of the samples cannot
954 be applied to CV results. In [63] methods for the analysis of compositional

955 data have been presented. The systematic review conducted as a part of this
956 study revealed that 22 studies analyze CV results; yet, only one study uses
957 compositional data analysis methods, i.e. [10]. None of the studies, including
958 [10], present methods for detecting items with equal priority in CV results.
959 Hence, ECV is, in this respect, a unique method.

960 The small use of compositional data analysis is really not surprising, since
961 literature describing CV does not state that the results are compositional
962 data. Standard statistical analysis methods may produce useful results for
963 compositional data. However, there are cases when they are misleading or
964 even faulty. Section 7.2.1 contains evidence of inappropriate use of statistical
965 methods by several papers.

966 This study has collected a set of compositional data analysis methods for
967 CV analysis (see Table 13). We believe that this could help researchers to
968 improve the analysis of CV results with appropriate methods.

969 Since CV is associated with compositional data, it might be tempting to
970 choose another requirements prioritization method. However, it would not
971 solve the problem *per se*, because any ratio scale prioritization, for instance
972 AHP, contains compositional data.

973 The principal implications for the academia are mainly the following:

- 974 1. All systematic literature reviews should include snowball sampling.
- 975 2. Researchers can improve their statistical analysis of CV results using
976 compositional data analysis methods collected and developed by this
977 study.
- 978 3. When CV or any other ratio scale prioritization method is taught,
979 compositional data analysis should also be presented as part of the
980 solution.

981 8.3. *Validity Threats*

982 The validity of the systematic review is mainly limited by the chosen
983 databases, the design of the review, and human judgement in study selection
984 and data extraction.

985 To mitigate the threats we use the most popular databases in the field
986 of software engineering. In the beginning of the systematic review a re-
987 view protocol was developed, peer-reviewed, and revised. Search strategy
988 was validated against a set of previously known papers obtained from other
989 researchers.

990 One of many terms used to name cumulative voting is ‘\$100 method’. We
991 were not able to search for this term because non of the chosen databases sup-
992 port search for special characters like ‘\$’ and the search string ‘100 method’
993 yields too many hits. To increase the likelihood of discovering relevant studies
994 snowball sampling was extensively used.

995 To increase the validity of study selection, all included studies and 20
996 randomly selected excluded studies were examined by two researchers. There
997 were no disagreement on the inclusion/exclusion of the studies.

998 The large number of studies identified by snowball sampling (15 out of
999 40 studies) may be caused by faulty design or by faulty execution of the
1000 search in the databases. There are several reasons why the studies revealed
1001 by snowball sampling are not revealed by the search in databases. (Reason
1002 for each study is given in Table Appendix A.2.) Based on these reasons we
1003 argue that snowball sampling does not indicate any problems with the design
1004 of the search in the databases.

1005 Four studies were not found because they were not available through
1006 databases used in this systematic review. Out of them one is a master thesis,
1007 two are conference publications and one is a publication in the area of forestry.
1008 Seven studies do not mention the name of the prioritization method (i.e.
1009 hundred dollar method or cumulative voting). Only phrases like “distribution
1010 of a predefined amount of fictitious money (\$100,000) over the items to be
1011 prioritized” or “1,000 points” allowed us to identify that CV was indeed
1012 used. One paper used a previously unknown name for CV, i.e. the 100-point
1013 technique.

1014 The quality of the data extraction and quality evaluation was validated
1015 using inter-rater agreement analysis. In our case, 10% of the studies were
1016 rated by two researchers and Krippendorff’s alpha was calculated. The agree-
1017 ment for the data extraction results was 0.86 and the agreement for the
1018 quality evaluation was 0.73 (indicating a credible level of quality).

1019 There are two main validity threats with ECV itself. First, ECV may not
1020 detect prioritization items with equal priority. Second, ECV may produce a
1021 false positive result, i.e. there may be a real difference between items that
1022 ECV claims as being equal.

1023 To mitigate the first threat ECV was applied on artificially created test
1024 data with and without items with similar priority. ECV worked correctly in
1025 both cases.

1026 To mitigate the second threat we visually inspected the results of the
1027 application of ECV on the real world data from the primary studies. We

concluded that items identified by ECV can be considered equal.

CV results used in the evaluation of ECV were tested for normality. The tests indicated that CV results do not have multivariate normal distribution. Therefore, the design of ECV was based on a non-parametric statistical test.

8.4. Future Work

With respect to future work one can distinguish two interesting paths: Scalability and improvements to ECV.

First, there are very few studies that apply CV on prioritization sets of more than 30 items. However, in requirements engineering, industry practitioners need to prioritize much larger numbers of software requirements. Therefore, the state of art could benefit from the application of CV and HCV to large prioritization sets.

The proposed method, ECV, has now been evaluated on existing research data. To further evaluate ECV, it would be appropriate to apply it in direct industry practice and in prioritization cases with a larger number of prioritization items (>30). Additionally, compositional data analysis methods, as the ones identified by this paper, should be tried with other prioritization methods that produce ratio scale results.

Second, ECV may be improved to find groups of equal items not just pairs. Equality of a pair (or a group) of items to another item can be tested with the help of compositional balances.

The CV process itself can also be improved with the help of compositional data analysis. Weighting of stakeholder priorities could be done using compositional powering, which could be presumed as better compared to using a multiplication that is removed in a log-ratio transformation.

Additionally, compensation of priority values in HCV is not *subcompositionally coherent*; thus, sequential binary partition could quite possibly be used to improve the compensation.

8.5. Conclusions

CV prioritization results are special type of data – compositional data. Any analysis of CV results must take into account the compositional nature of the CV results.

This study presents a systematic literature review of the empirical use of CV. CV has been applied in various areas, but most frequently in requirements prioritization and release planning. The review has resulted in

a collection of state of the practice studies and CV result analysis methods. We believe that it can help the adoption of CV prioritization method.

In our case, snowball sampling was performed as a part of the review. Since it revealed 36% out of all primary studies, we believe that in future snowball sampling should be used in all systematic reviews.

Additionally, we present ECV—a novel method for CV analysis. As suggested by our evaluation, ECV is able to detect prioritization items with equal priority (i.e. items that have insignificant difference in priority). The evaluation of ECV was based on the data obtained from the authors of the primary studies.

References

- [1] P. Berander, A. Andrews, Requirements prioritization, in: A. Aurum, C. Wohlin (Eds.), *Engineering and managing software requirements*, Springer-Verlag, Berlin/Heidelberg, 2005, pp. 69–94.
- [2] D. Leffingwell, D. Widrig, *Managing software requirements: A unified approach*, Addison-Wesley Professional, 1999.
- [3] V. Ahl, An experimental comparison of five prioritization methods, Master's Thesis, School of Engineering, Blekinge Institute of Technology, Sweden.
- [4] P. Berander, P. Jönsson, Hierarchical cumulative voting (HCV) - Prioritization of requirements in hierarchies, *International Journal of Software Engineering and Knowledge Engineering* 16 (6) (2006) 819–850.
- [5] J. Karlsson, K. Ryan, A cost-value approach for prioritizing requirements, *IEEE Software* 14 (5) (1997) 67–74.
- [6] J. Karlsson, An evaluation of methods for prioritizing software requirements, *Information and Software Technology* 39 (14-15) (1998) 939–947.
- [7] F. Pettersson, M. Ivarsson, T. Gorschek, P. Öhman, A practitioner's guide to light weight software process assessment and improvement planning, *Journal of Systems and Software* 81 (2008) 972–995.
- [8] S. Barney, C. Wohlin, Software product quality: Ensuring a common goal, in: Q. Wang, V. Garousi, R. Madachy, D. Pfahl (Eds.), *Trustworthy Software Development Processes*, Vol. 5543 of *Lecture Notes in*

- 1095 Computer Science, Springer-Verlag, Berlin, Heidelberg, 2009, pp. 256–
1096 267.
- 1097 [9] P. Jönsson, C. Wohlin, A study on prioritisation of impact analysis
1098 issues: A comparison between perspectives, *Software Engineering Re-*
1099 *search and Practice in Sweden*.
- 1100 [10] P. Chatzipetrou, L. Angelis, P. Rovegard, C. Wohlin, Prioritization of
1101 issues and requirements by cumulative voting: A compositional data
1102 analysis framework, in: *Proceedings of the 2010 36th EUROMICRO*
1103 *Conference on Software Engineering and Advanced Applications*, IEEE
1104 Computer Society, Washington, DC, USA, 2010, pp. 361–370.
- 1105 [11] R. L. Engstrom, D. A. Taebel, R. L. Cole, Cumulative voting as a rem-
1106 edy for minority vote dilution: The case of Alamogordo, New Mexico,
1107 *Journal of Law & Politics* 5 (1988) 469–497.
- 1108 [12] S. Bhagat, J. A. Brickley, Cumulative voting: The value of minority
1109 shareholder voting rights, *Journal of Law and Economics* 27 (2) (1984)
1110 339–365.
- 1111 [13] V. Hiltunen, J. Kangas, J. Pykalainen, Voting methods in strategic forest
1112 planning - Experiences from Metsähallitus, *Forest Policy and Economics*
1113 10 (3) (2008) 117–127.
- 1114 [14] P. Boldi, F. Bonchi, C. Castillo, S. Vigna, Voting in social networks, in:
1115 *Proceedings of the 18th ACM conference on Information and knowledge*
1116 *management*, ACM, New York, NY, USA, 2009, pp. 777–786.
- 1117 [15] H. Ayad, M. Kamel, Cumulative voting consensus method for partitions
1118 with variable number of clusters, *IEEE Transactions on Pattern Analysis*
1119 *and Machine Intelligence* 30 (1) (2008) 160–173.
- 1120 [16] M. Svahnberg, A. Karasira, A study on the importance of order in re-
1121 quirements prioritisation, in: *Proceedings of the Third International*
1122 *Workshop on Software Product Management*, IEEE Computer Society,
1123 Washington, DC, USA, 2009, pp. 35–41.
- 1124 [17] P. Berander, M. Svahnberg, Evaluating two ways of calculating priorities
1125 in requirements hierarchies - An experiment on hierarchical cumulative
1126 voting, *Journal of Systems and Software* 82 (2009) 836–850.

- 1127 [18] T. L. Saaty, The analytic hierarchy process, McGraw-Hill, New York,
1128 1980.
- 1129 [19] J. Aitchison, J. J. Egozcue, Compositional Data Analysis: Where Are
1130 We and Where Should We Be Heading?, *Mathematical Geology* 37 (7)
1131 (2005) 829–850.
- 1132 [20] V. Pawlowsky-Glahn, J. J. Egozcue, Compositional data and their anal-
1133 ysis: An introduction, Geological Society, London, Special Publications
1134 264 (1) (2006) 1–10.
- 1135 [21] J. A. Martín-Fernández, C. Barceló-Vidal, V. Pawlowsky-Glahn, Deal-
1136 ing with zeros and missing values in compositional data sets using non-
1137 parametric imputation, *Mathematical Geology* 35 (3) (2003) 253–278.
- 1138 [22] P. Filzmoser, K. Hron, Outlier detection for compositional data using
1139 robust methods, *Mathematical Geosciences* 40 (2008) 233–248.
- 1140 [23] S. Laukkanen, T. Palander, J. Kangas, Applying voting theory in par-
1141 ticipatory decision support for sustainable timber harvesting, *Canadian*
1142 *Journal of Forest Research* 34 (7) (2004) 1511–1524.
- 1143 [24] D. Cooper, A. Zillante, A comparison of cumulative voting and gener-
1144 alized plurality voting, *Public Choice* 150 (1-2) (2010) 363–383.
- 1145 [25] A. Hoover, M. Goldbaum, Locating the optic nerve in a retinal image
1146 using the fuzzy convergence of the blood vessels, *Medical Imaging, IEEE*
1147 *Transactions on* 22 (8) (2003) 951–958.
- 1148 [26] V. Heikkilä, A. Jadallah, K. Rautiainen, G. Ruhe, Rigorous support for
1149 flexible planning of product releases - A stakeholder-centric approach
1150 and its initial evaluation, in: 2010 43rd Hawaii International Conference
1151 on System Sciences, IEEE Computer Society, 2010, pp. 1–10.
- 1152 [27] D. Baca, K. Petersen, Prioritizing countermeasures through the coun-
1153 termeasure method for software security (CM-Sec), in: M. Ali Babar,
1154 M. Vierimaa, M. Oivo (Eds.), *Product-Focused Software Process Im-*
1155 *provement*, Vol. 6156 of *Lecture Notes in Computer Science*, Springer-
1156 *Verlag*, Berlin, Heidelberg, 2010, pp. 176–190.

- 1157 [28] P. Berander, P. Jönsson, A goal question metric based approach for ef-
1158 ficient measurement framework definition, in: Proceedings of the 2006
1159 ACM/IEEE international symposium on Empirical software engineer-
1160 ing, ACM, New York, NY, USA, 2006, pp. 316–325.
- 1161 [29] R. Feldt, R. Torkar, E. Ahmad, B. Raza, Challenges with software ver-
1162 ification and validation activities in the space industry, in: Proceedings
1163 of the 2010 Third International Conference on Software Testing, Verifi-
1164 cation and Validation, IEEE Computer Society, Washington, DC, USA,
1165 2010, pp. 225–234.
- 1166 [30] M. Svahnberg, T. Gorschek, M. Eriksson, A. Borg, K. Sandahl,
1167 J. Börster, A. Loconsole, Perspectives on requirements understandabil-
1168 ity – For whom does the teacher’s bell toll?, in: Proceedings of the 2008
1169 Requirements Engineering Education and Training, IEEE Computer So-
1170 ciety, Washington, DC, USA, 2008, pp. 22–29.
- 1171 [31] J. Aitchison, The statistical analysis of compositional data, *Journal of*
1172 *the Royal Statistical Society. Series B (Methodological)* 44 (2) (1982)
1173 139–177.
- 1174 [32] J. Egozcue, V. Pawlowsky-Glahn, G. Mateu-Figueras, C. Barceló-
1175 Vidal, Isometric logratio transformations for compositional data analy-
1176 sis, *Mathematical Geology* 35 (3) (2003) 279–300.
- 1177 [33] K. Khan, A systematic review of software requirements prioritization,
1178 Master’s thesis, Blekinge Institute of Technology, Ronneby, Sweden.
- 1179 [34] F. Zahedi, The analytic hierarchy process: A survey of the method and
1180 its applications, *Interfaces* 16 (4) (1986) 96–108.
- 1181 [35] P. Runeson, M. Höst, Guidelines for conducting and reporting case study
1182 research in software engineering, *Empirical Software Engineering* 14 (2)
1183 (2008) 131–164.
- 1184 [36] L. Goodman, Snowball sampling, *The Annals of Mathematical Statistics*
1185 32 (1) (1961) 148–170.
- 1186 [37] K. Krippendorff, Bivariate agreement coefficients for reliability of data,
1187 *Sociological Methodology* 2 (1970) 139–150.

- 1188 [38] K. Krippendorff, Content analysis: An introduction to its methodology,
1189 2nd Edition, Sage Publications, 2003.
- 1190 [39] B. Kitchenham, S. Charters, Guidelines for performing systematic liter-
1191 ature reviews in software engineering, Tech. Rep. EBSE 2007-001, Keele
1192 University (2007).
- 1193 [40] B. Regnell, M. Höst, J. Natt och Dag, P. Beremark, T. Hjelm, An
1194 industrial case study on distributed prioritisation in market-driven re-
1195 quirements engineering for packaged software, Requirements Engineer-
1196 ing 6 (1) (2001) 51–62.
- 1197 [41] B. Kitchenham, Procedures for performing systematic reviews, Tech.
1198 Rep. TR/SE-0401, Keele University (2004).
- 1199 [42] M. Ivarsson, T. Gorschek, A method for evaluating rigor and industrial
1200 relevance of technology evaluations, Empirical Software Engineering 16
1201 (2011) 365–395.
- 1202 [43] C. Wohlin, P. Runeson, M. Höst, Experimentation in software engineer-
1203 ing: An introduction, Springer Netherlands, 2000.
- 1204 [44] A. Jedlitschka, D. Pfahl, Reporting guidelines for controlled experiments
1205 in software engineering, in: Proceedings of the 2005 International Sym-
1206 posium on Empirical Software Engineering, IEEE Computer Society,
1207 2005, pp. 95–104.
- 1208 [45] K. Rinkevics, R. Torkar, Data extraction and quality evaluation results
1209 (2011).
1210 URL [http://rinkevic.wordpress.com/2011/11/26/
1211 data-extraction-and-quality-evaluation-results/](http://rinkevic.wordpress.com/2011/11/26/data-extraction-and-quality-evaluation-results/)
- 1212 [46] R. Ihaka, R. Gentleman, R: A language for data analysis and graphics,
1213 Journal of computational and graphical statistics 5 (3) (1996) 299–314.
- 1214 [47] K. Rinkevics, R. Torkar, ECV implementation source code in R (2011).
1215 URL [http://rinkevic.wordpress.com/2011/08/14/
1216 ecv-implementation-in-r/](http://rinkevic.wordpress.com/2011/08/14/ecv-implementation-in-r/)
- 1217 [48] R. M. Groves, F. J. Fowler, M. P. Couper, J. M. Lepkowski, E. Singer,
1218 Survey methodology, John Wiley and Sons, 2009.

- 1219 [49] S. Barney, A. Aurum, C. Wohlin, The relative importance of aspects
1220 of intellectual capital for software companies, in: Proceedings of the
1221 2009 35th Euromicro Conference on Software Engineering and Advanced
1222 Applications, IEEE Computer Society, 2009, pp. 313–320.
- 1223 [50] S. Barney, C. Wohlin, Software product quality: Ensuring a common
1224 goal, in: Proceedings of the International Conference on Software Pro-
1225 cess: Trustworthy Software Development Processes, Springer-Verlag,
1226 Berlin, Heidelberg, 2009, pp. 256–267.
- 1227 [51] S. Barney, A. Aurum, C. Wohlin, A product management challenge:
1228 Creating software product value through requirements selection, *Journal*
1229 *of Systems Architecture* 54 (6) (2008) 576–593.
- 1230 [52] S. Laukkanen, T. Palander, J. Kangas, A. Kangas, Evaluation of the
1231 multicriteria approval method for timber-harvesting group decision sup-
1232 port, *Silva Fennica* 39 (2) (2005) 249–264.
- 1233 [53] G. Hu, A. Aurum, C. Wohlin, Adding value to software requirements:
1234 An empirical study in the Chinese software industry, in: Proceedings of
1235 the Seventeenth Australasian Conference on Information Systems, 2006.
- 1236 [54] P. Jönsson, C. Wohlin, Understanding impact analysis: An empiri-
1237 cal study to capture knowledge on different organisational levels, in:
1238 Proceedings of International Conference on Software Engineering and
1239 Knowledge Engineering, IEEE Computer Society, 2005, pp. 707–712.
- 1240 [55] L. Kuzniarz, L. Angelis, Empirical extension of a classification frame-
1241 work for addressing consistency in model based development, *Informa-*
1242 *tion and Software Technology* 53 (2011) 214–229.
- 1243 [56] P. Rovegard, L. Angelis, C. Wohlin, An empirical study on views of im-
1244 portance of change impact analysis issues, *IEEE Transactions on Soft-*
1245 *ware Engineering* 34 (4) (2008) 516–530.
- 1246 [57] C. Wohlin, A. Aurum, Criteria for selecting software requirements to cre-
1247 ate product value: An industrial empirical study, in: S. Biffl, A. Aurum,
1248 B. Boehm, H. Erdogan, P. Grünbacher (Eds.), *Value-based software en-*
1249 *gineering*, Springer-Verlag, Berlin, Heidelberg, 2006, pp. 179–200.

- 1250 [58] B. Regnell, M. Höst, J. Natt och Dag, Visualization of agreement and
1251 satisfaction in distributed prioritization of market requirements, in: Pro-
1252 ceedings of REFSQ2000, 6th Int. Workshop on Requirements Engineering
1253 ing: Foundation for Software Quality, 2000, pp. 1–12.
- 1254 [59] J. Aitchison, Principal component analysis of compositional data,
1255 *Biometrika* 70 (1) (1983) 57–65.
- 1256 [60] P. Filzmoser, K. Hron, C. Reimann, Principal component analysis for
1257 compositional data with outliers, *Environmetrics* 20 (6) (2009) 621–632.
- 1258 [61] V. Pawlowsky Glahn, J. Egozcue, R. Tolosana Delgado, Lecture notes
1259 on compositional data analysis, Tech. rep., Universitat de Girona, Spain
1260 (July 2007).
- 1261 [62] W. H. Kruskal, W. A. Wallis, Use of ranks in one-criterion variance
1262 analysis, *Journal of the American Statistical Association* 47 (260) (1952)
1263 583–621.
- 1264 [63] J. Aitchison, *The statistical analysis of compositional data*, Chapman
1265 & Hall, London, 1986.
- 1266 [64] S. Bowler, D. Brockington, T. Donovan, Election systems and voter
1267 turnout: Experiments in the United States, *The Journal of Politics*
1268 63 (3) (2001) 902–915.
- 1269 [65] D. Brockington, A low information theory of ballot position effect, *Pol-
1270 itical Behavior* 25 (1) (2003) 1–27.
- 1271 [66] N. Dzamashvili Fogelström, M. Svahnberg, T. Gorschek, Investigating
1272 impact of business risk on requirements selection decisions, in: Proceed-
1273 ings of the 2009 35th Euromicro Conference on Software Engineering
1274 and Advanced Applications, IEEE, 2009, pp. 217–223.
- 1275 [67] S. Hatton, Choosing the right prioritisation method, in: Proceedings of
1276 the 19th Australian Conference on Software Engineering, IEEE Com-
1277 puter Society, Washington, 2008, pp. 517–526.
- 1278 [68] S. Hatton, Early prioritisation of goals, in: Proceedings of the 2007
1279 Conference on Advances in Conceptual Modeling: Foundations and Ap-
1280 plications, Springer-Verlag, Berlin, Heidelberg, 2007, pp. 235–244.

- 1281 [69] M. Staron, C. Wohlin, An industrial case study on the choice between
1282 language customization mechanisms, in: J. Münch, M. Vierimaa (Eds.),
1283 Product-Focused Software Process Improvement, Vol. 4034 of Lecture
1284 Notes in Computer Science, Springer-Verlag, Berlin, Heidelberg, 2006,
1285 pp. 177–191.
- 1286 [70] T. Touseef, C. Gencel, A structured goal based measurement framework
1287 enabling traceability and prioritization, in: Proceedings of the 2010 6th
1288 International Conference on Emerging Technologies, 2010, pp. 282–286.
- 1289 [71] P. Berander, C. Wohlin, Differences in views between development roles
1290 in software process improvement - A quantitative comparison, in: Pro-
1291 ceedings of the 8th International Conference on Empirical Assessment in
1292 Software Engineering, 2004.
- 1293 [72] P. Berander, Using students as subjects in requirements prioritization,
1294 in: Proceedings of the 2004 International Symposium on Empirical Soft-
1295 ware Engineering, IEEE Computer Society, 2004, pp. 167–176.
- 1296 [73] P. Berander, C. Wohlin, Identification of key factors in software process
1297 management - A case study, in: Proceedings of the 2003 International
1298 Symposium on Empirical Software Engineering, IEEE Computer Soci-
1299 ety, Washington, DC, USA, 2003, pp. 316–325.
- 1300 [74] R. L. Cole, D. A. Taebel, R. L. Engstrom, Cumulative voting in a mu-
1301 nicipal election: A note on voter reactions and electoral consequences,
1302 The Western Political Quarterly 43 (1) (1990) 191–199.
- 1303 [75] J. Kuklinski, Cumulative and plurality voting: An analysis of Illinois’
1304 unique electoral system, The Western Political Quarterly 26 (4) (1973)
1305 726–746.
- 1306 [76] J. Sawyer, D. MacRae, Game theory and cumulative voting in Illinois:
1307 1902-1954, The American Political Science Review 56 (4) (1962) 936–
1308 946.

1309 Appendix A. Primary Studies

1310 Appendix A.1. Primary studies found in databases.

Title	Reference
Prioritizing countermeasures through the countermeasure method for software security (CM-Sec)	Baca 2010 [27]
The relative importance of aspects of intellectual capital for software companies	Barney 2009 [49]
Software product quality: Ensuring a common goal	Barney 2009 [8]
Balancing software product investments	Barney 2009 [50]
Hierarchical cumulative voting (HCV) prioritization of requirements in hierarchies	Berander 2006 [4]
A goal question metric based approach for efficient measurement framework definition	Berander 2006 [28]
Evaluating two ways of calculating priorities in requirements hierarchies: An experiment on hierarchical cumulative voting	Berander 2009 [17]
Election systems and voter turnout: Experiments in the United States	Bowler 2001 [64]
A low information theory of ballot position effect	Brockington 2003 [65]
Prioritization of issues and requirements by cumulative Voting: A compositional data analysis framework	Chatzipetrou 2010 [10]
A comparison of cumulative voting and generalized plurality voting	Cooper 2010 [24]
Challenges with software verification and validation activities in the space industry	Feldt 2010 [29]
Investigating impact of business risk on requirements selection decisions	Fogelstrom 2009 [66]
Choosing the right prioritization method	Hatton 2008 [67]
Early prioritization of goals	Hatton 2007 [68]
Rigorous support for flexible planning of product releases: A stakeholder-centric approach and its initial evaluation	Heikkila 2010 [26]
Voting methods in strategic forest planning: Experiences from Metsähallitus	Hiltunen 2008 [13]
Empirical extension of a classification framework for addressing consistency in model based development	Kuzniarz 2010 [55]
Evaluation of the multi-criteria approval method for timber-harvesting group decision support	Laukkanen 2005 [52]
A practitioner's guide to light weight software process assessment and improvement planning	Pettersson 2008 [7]
An empirical study on views of importance of change impact analysis issues	Rovegard 2008 [56]
An industrial case study on the choice between language customization mechanisms	Staron 2006 [69]
Perspectives on requirements understandability—For whom does the teacher's bell toll?	Svahnberg 2008 [30]
A study on the importance of order in requirements prioritization	Svahnberg 2009 [16]
A structured goal based measurement framework enabling traceability and prioritization	Touseef 2010 [70]

1312 Appendix A.2. Primary studies revealed by snowball sampling.

Reference	Title	Reason why the paper is not revealed by the search in databases
Ahl 2005 [3]	An experimental comparison of five prioritization methods	Selected databases does not contain the paper, master thesis at BTH
Barney 2008 [51]	A product management challenge: Creating software product value through requirements selection	Prioritization method name not mentioned, phrase "1,000 points" used instead.
Berander 2004 [71]	Differences in views between development roles in software process improvement—A quantitative comparison	Prioritization method name not mentioned, phrase "100 points" used instead.
Berander 2004 [72]	Using students as subjects in requirements prioritization	Unknown CV name: 100-point technique
Berander 2003 [73]	Identification of key factors in software process management: A case study	Prioritization method name not mentioned, phrase "100 points" used instead.
Cole 1990 [74]	Cumulative voting in a municipal election: A note on voter reactions and electoral consequences	Study published before year 2001.
Hu 2006 [53]	Adding value to software requirements: An empirical study in the chinese software industry	Prioritization method name not mentioned, phrase "1,000 points" used instead.
Jonsson 2005 [9]	A study on prioritization of impact analysis issues: A comparison between perspectives	Selected databases does not contain the paper.
Jonsson 2005 [54]	Understanding impact analysis: An empirical study to capture knowledge on different organizational levels	Selected databases does not contain the paper.
Kuklinski 1973 [75]	Cumulative and plurality voting: An analysis of Illinois' unique electoral system	Study published before year 2001.
Laukkanen 2004 [23]	Applying voting theory in participatory decision support for sustainable timber harvesting	Selected databases does not contain the paper.
Regnell 2001 [40]	An industrial case study on distributed prioritization in market-driven requirements engineering for packaged software	Prioritization method name not mentioned: "distribution of a predefined amount of fictitious money (\$100,000) over the items to be prioritized."
Regnell 2000 [58]	Visualization of agreement and satisfaction in distributed prioritization of market requirements	Prioritization method name not mentioned: "distribution of a predefined amount of fictitious money (\$100,000) over the items to be prioritized."
Wohlin 2006 [76]	Game theory and cumulative voting in Illinois: 1902–1954	Study published before year 2001.
Wohlin 2006 [57]	Criteria for selecting software requirements to create product value: An industrial empirical study	Prioritization method name not mentioned: "The subjects had 1,000 points to spend among the 13 criteria."

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Appendix B. CV Result Analysis Methods

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	Paper															
	Svahnberg2008	Svahnberg2009	Storon2006	Pettersen2008	Wöhlin2006	Lanklaen2005a	Hu2006	Jonsson2005a	Kuzniarz2010	Rovgaard2008	Berander2006a	Berander2004a	Berander2006	Feldt2010	Barney2006b	Barney2008
Analysis method																
Table that shows final priorities	x			x											x	
Chart that shows final priorities	x			x	x	x	x									
Table of top-5 prioritization items								x								
min, max, \bar{x} , $\bar{\sigma}$ and σ of priorities assigned by different stakeholders									x	x						
Bar chart of prioritization results showing \bar{x} priority and σ of priorities									x	x						
Pearson correlation coefficient		x									x					
Nemenyi Damico Wolfe Dunn													x			
Spearman's r														x		
Kruskal-Wallis								x							x	
Wilcoxon							x									
Correlation matrix	x													x	x	
Chart for comparing priorities from two perspectives, priorities are points in two dimensional plane, x - and y -axis represent two different perspectives										x						
Difference between priorities assigned by each two stakeholders using χ^2 -statistic										x						
Median ranks	x															
CV results converted to priority ranks	x												x			
PCA				x	x											
Percentage of divergence of priorities assigned by a stakeholder																
Average percentage of items given non-zero value										x						
Distribution chart										x						
Disagreement chart				x												
Satisfaction chart				x												
Bi-plot																
Ternary plot																

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Appendix C. Quality Evaluation Checklist

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	Item	Question or Description of the Item	Rating
1.	Background, introduction	Introduce research area	
2.	Problem statement, purpose	What is the problem [44]? Where does it occur [44]? Who has observed it [44]? Why is it important to be solved [44]?	
3.	Context, independent variables (aka. environment, setting)	Study location, time constraints, application domain, organization, tools, market, process (e.g. software development methodology), size of project, product that is being developed	
4.	Related work	Other existing work, alternative technologies, solutions, and studies	
5.	Goals and Hypotheses	Null hypothesis and one or more alternative hypotheses for each goal	
6.	Research questions		
7.	Design, Research methods		
7.1.	Design	Description of each step of the study	
7.2.	Control group	If there is a control group, are participants similar to the treatment group participants in terms of variables that may affect study outcomes[39]?	
7.3.	Randomization	Random selection of participants and objects Random assignment of treatment and objects to participants Random order of treatments in case of paired design. If each participant is assigned two treatments A and B, then part of participants perform A first and the other part start with B	
7.4.	Blocking	Group participants of the study into homogeneous groups called blocks (e.g. students in one course, database developers in one company) and implement the study design within each block independently. The idea is that variability of independent variables (e.g. experience and knowledge of subjects) is smaller within a group. That helps measuring changes in dependent variables [41].	
7.5.	Balancing	Equal number of subjects should be assigned to each treatment [41].	
7.6.	Blinding	Automated assignment of treatments to subjects [41] Automated distribution of study materials to subjects [41] Persons who grade the task results should not know which treatment was used [41] Analyst should not know which treatment group is which [41] Automated data collection from subjects [41]	
8.	Subjects (participants)		
8.1.	Population		
8.2.	Sampling	How sampling is performed? What subjects are included and excluded? [39] What is the type of the sampling (e.g. convenience, random)? Is the sample(selected participants) representative of the population?	
8.3.	"Drop outs" and response rate	Are reasons given for refusal to participate[39]?	
8.4.	Subject motivation	E.g. material benefits, course credits for students, etc.	
9.	Objects	E.g. documents and other artifacts	
10.	Measures, Data collection procedures	Who, when, and how to measure [39]? How is the measurement supported? Is it automated [39]? Are the measures used in the study the most relevant ones for answering the research questions [39]?	
11.	Analysis procedure		
11.1.	Data description	Do the numbers add up across different tables and subgroups [39]?	
11.2.	Data types (continuous, ordinal, categorical)		
11.3.	Scoring systems		
11.4.	Data set reduction, outliers		
11.5.	Statistical methods	Are the assumptions of statistical methods met?	
11.6.	Statistical significance	If statistical tests are used to determine differences, is the actual p -value given [39]? If the study is concerned with differences among groups, are confidence limits given describing the magnitude of any observed differences [39]?	
12.	Validity threats	Threats, implications of the threats, and threat mitigation	
12.1.	Side-effects during study execution	Deviations from the plan, solutions for the deviations	
13.	Most important findings	Are all study questions answered [39]? Are negative findings presented [39]?	
14.	Industry impact, inference, generalization	What implications does the report have for practice [39]? How and where the results can be used? Limitations under which findings are relevant [44]?	
15.	Future work		