World's Best Universities and Personalized Rankings

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Abstract

This chapter presents a heuristic for a multi-objective ranking problem using a dataset of international interest as an example of its application, namely, the ranking of the world's top educational institutions. The problem of ranking academic institutions is a subject of keen interest for administrators, consumers, and research policy makers. From a mathematical perspective, the proposed heuristic addresses the need for more transparent models and associated methods related to the problem of identifying sound relative rankings of objects with multiple attributes. The low complexity of the method allows software implementations that scale well for thousands of objects as well as permitting reasonable visualization. It is shown that a simple and multi-objective-aware ranking system can easily be implemented, which naturally leads to intuitive research policies resulting from varying scenarios presented within. The only assumption that this method relies on is the ability to sort the candidate objects according to each given attribute. Thus the attributes could be numerical or ordinal in nature. This helps to avoid the selection of an ad hoc single score based on an arbitrary assignment of attributes' weights as other heuristics do. To illustrate the use of this proposed methodology, results are presented and obtained using the dataset on the ranking of world universities (of the years 2007–2012), by academic performance, published annually by ARWU.

Keywords

Analytics · Digital humanities · Pareto optimality · Ranking · Symbolic regression

Introduction

Ranking multi-attributed objects is ubiquitous in the twenty-first century. This is not an overstatement. Every time people use a web search engine and query it using a particular keyword or phrase, a ranked list of webpages appears on our screen. This ranking is automatic, in most cases deterministic, and is well defined in mathematical terms. Not only the speed but the quality of the ranking may decide the fate of the company that has created that search engine. Every time people read a newspaper, or watch television, the news stories provided have been edited, and the core subject has been ranked and selected. Today, our governments want to decide on spending based on the objective rankings of institutions, their quality, performance, and delivery of service.

Specifically, the ranking of educational institutions has received increasing interest from scholars, policy developers, and strategic decision-makers worldwide. Our society, regardless of nationality, enjoys (and in some cases needs) to rank tennis players, sport teams, health systems, supercomputers, economical performance, scientists' achievements, most and least "liveable" countries and cities, restaurants, waiting lists for surgery and transplantation [2], targets in structure-based virtual screening of three-dimensional protein libraries [30], genes in microarray experiments [6, 32] or in association studies [58], athletic training education programs [63], pedestrian crash zones [47], stressfulness of joints and joint motions in ergonomics applications [29], movie stars, dental esthetics [8]), and even US presidents.

The academic ranking of world universities follows the general trend of globalization of the economy. Researchers agree that ranking global universities is attracting increasing attention as it is a topic of high interest to many different stakeholders; see, for instance, [7, 34, 39, 40], among others. If you look at universities as service providers and if their potential students are free to choose among a variety of them, it is natural to pay attention to rankings to help them select the best tailored to their interests. This has become of even greater importance in recent years due to the increased mobility of students, researchers, and staff [52]. Furthermore, strategic decision-making within institutions, and policy development at a larger scale, relies on the provision of useful information regarding an institution's quality, excellence, and global ranking position.

Needless to say, ranking global universities is a quest of great impact and social significance [59]; however, the methodologies proposed are naive at best. It could be said that the problem is inherently *ill posed*. First, outcomes of ranking activities should be user centric. A student who has to choose where to go for graduate school studies may be more interested in the quality of their specific disciplines that constitute the core set of knowledge she is looking for and may dismiss an institution that has Nobel Prize winners lecturing using chalk and a blackboard (see [20] for a discussion on how to define quality). Managers and strategic decision-makers need to have access to information about how their institution benchmarks against their "competitors" in order to successfully and optimally allocate their resources and funds. Furthermore, it is important to remember that different stakeholders have different expectations about quality [34] and different expectations of an educational institution in general. In essence, it is important to highlight that ranking systems should be developed allowing the various users of these systems to easily add or remove an attribute of the objects in order to suit their specific needs and interests.

The request of [24] "*...there is still a dearth of peer-reviewed scientific publications on international ranking methods. Raw data and several key details about the methodology still remain unavailable to public scrutiny.*" [24] easily resonates with this study. In addition to this, it recognized that the trustworthiness of many ranking systems is sensitive to the conceptual framework (its indicators) as well as the modeling choices such as weighting of indicators [52]. In order to fill this methodological gap, the issue of academic rankings of universities is addressed as an illustrative test case. This chapter thus aims to differ from Ioannidis et al. who have well articulated their case for the importance of a common international consensus on the validity of the measured attributes for each institution. The methodology presented here moves away from the traditional comparison of one-dimensional lists between ranked objects.

In this chapter other metrics that can be computed are included as well as a very simple heuristic that, using raw data, allows users to select/deselect attributes to better target their interests. This approach can “tailor” a ranking system according to the user’s individual preferences. Therefore, this system naturally provides a user-centric experience, while it is still based on quantitative nonsubjective information. This said, while this chapter is focussed on the largest online dataset of universities’ performance, its final aim is to exemplify on its use to address the multi-objective ranking problem from a general methodological standpoint. In this method, the issue of sensitivity due to arbitrarily assigning of weights to indicators is addressed and the problems that arise in doing so, rather than using raw data.

The chapter is organized as follows. Section “Materials and Methods” illustrates where the data was obtained from, a brief description of the data, and an outline of the methodology used. Section “Results” has several subsections in order to display the results. Results for the computation of the dominance graph for the period 2007–2009 are displayed in section “University Ranking Results 2007–2009” followed by results describing transitive dominance as well as the implementation of symbolic regression modeling (section “Transitive Dominance Example Results”), mobility of universities in ranking (section “Sensitivity Analysis of Mobility over the Period 2010–2012”), and case examples of various universities, and, finally, a brief discussion on the attribute *Alumni* is included in section “The Case of the Alumni Attribute”. Section “Discussion” provides a discussion of the results and includes the limitations thereof and recommendations for possible future areas of research.

Materials and Methods

To illustrate the proposed analysis methods for ranking, and to ensure reproducibility and interpretability of the results, the online publicly available information provided by the Academic Ranking of World Universities (ARWU) is used in this study. This is an annual publication and the data that is used for their ranking is provided by the Institute for Higher Education, Shanghai Jiao Tong University, since 2003.

Table 1 Explanation of the institute for higher education, Shanghai Jiao Tong University ranking system. Note that the attribute “Size” is also referred to as “Per Capita Performance” (PCP) and the attribute “SCI” is also referred to as “PUB” in various articles and resources

Attribute	Weighting	Explanation
Alumni	10%	Number of alumni of the institution winning Nobel Prizes and Fields Medals
Award	20%	Number of staff of the institution winning Nobel Prize and Field Medals categories
HiCi	20%	Number of highly cited researchers in 21 broad subjects
N&S	20%	Number of articles published in Nature or Science
SCI	20%	Articles in Science Citation Index Expanded, Social Science Citation Index, and Arts and Humanities Citation Index
Size	10%	Academic performance with respect to the size of the institution

The ARWU from the Shanghai Jiao Tong University is based on the performance of universities according to six categories (attributes). These attributes are displayed in Table 1 with their respective weighting given by the Shanghai Jiao Tong University and their explanations. The six attributes are *Alumni*, *Award*, *HiCi*, *N&S*, *SCI* (or PUB), and *Size* (or PCP). It is important to note that for institutions specializing in humanities and the social sciences, such as the London School of Economics, in the ARWU ranking systems, the attribute of N&S is not considered, and weighting is distributed to other indicators [34]. This borderline between institutions, however, is somewhat arbitrary. Therefore, it has to be recognized that for some institutions only four attributes (with arbitrary weighting) remain for consideration and that is a natural aspect of its organization on a reduced number of fields. In each category a university will receive a value between 0 and 100. The university with the best performance in a particular category receives the top value of a 100, and the rest of the universities will receive a proportional value against this measure. Further details and explanation of these attributes and the scoring procedure can be found on the Shangai Jiao Tong University ARWU website (http://www.shanghairanking.com) or in Liu et al. [34].

The raw data of this ranking process for the years 2007–2012 is used. From the top 500 universities in each year, only those that are present in all years since 2007 are included. This means that in total, the scores of 444 universities are used in the method. With this information, three datasets for analysis are created; one for the years 2007–2009, another for 2010–2012, and a combined dataset including the attributes over the whole six-year period. The first two are an array U of 444 rows and 18 columns, and each value in the array represents the score that the institution has in each of the six categories in the three years. The combined array has, of course, 36 columns.

The purpose of this chapter is not to argue the accurateness of this information, but rather utilize this data for an application of the method proposed. The reader should recognize that the use of this dataset has been challenged in terms of its reproducibility by Razvan [50] and also recognize the work by Docampo [14] who also alert of some problems in the ARWU's processes. However, as highlighted by many authors, after recognition of these issues and also noting the criticisms revolving about the ARWU ranking, this contribution addresses two of them. In particular, in section "Results", the *Alumni* attribute and the attribute related to *Size* (PCP) deserve two separate experiments to understand their contribution. On this point, it can be argued that, to ensure transparency, an international standard on the universities reporting on performance on specific attributes should be made available and that it is best, for reproducibility, to work with raw data. This said, this information is taken *bona fide*, as correct and complete.

From this set of attributes, other types of ranking systems could create other attributes or "meta-features" by combining or multiplying multiple attributes of the dataset. Typically, aggregates should be avoided whenever possible, and normalizations (e.g., dividing total number of publications by the total number of full-time employees) can easily be derived should this be required or desired by the user. Having said this, these standards may not make the dataset used in this study fully satisfactory (aggregates exist, normalization by full-time employees equivalents are not made, other problems have been identified in Ioannidis et al. [24]), but this dataset is one of the world's best, regarding its coverage, and serves to illustrate our proposed methodology.

Construction of a Dominance Graph and Transitive Reduction

The method proposed in this chapter uses concepts inspired by transitive dominance to build a directed acyclic graph (DAG) ($G(V, A)$). A university x dominates university y, if and only if, for each attribute i the values of the universities for this attribute satisify $x_i \geq y_i,\ \forall\ i\ :\ [1..m]\ \wedge\ \exists\ j\ \in [1..m]\ /\ x_j > y_j$. This means that the performance of university x is at least better or equal in all attributes than university y, with at least one attribute at having a higher value. This definition creates a DAG $G(V, A)$ where each vertex represents a university, and if there is an arc $a_{xy} \in A$, it means that university x dominates university y. Within this chapter it will be shown that this DAG naturally induces a hierarchy of universities, with universities at Level 1 being those that are *not* dominated by any other university in the set. Here it is implied that the notation $x_i \geq y_i$ is general in meaning and is valid for both numerical and ordinal attributes. It is assumed that the attributes' measures are selected in such a way that a higher value on them implies a higher standing. This is a strength of this method as it can deal with datasets of mixed attribute types.

The resulting graph of this procedure would be hard to visualize in two dimensions as there are 444 nodes and it is very dense. Therefore, in order to simplify the DAG, without losing the hierarchy created, a method similar to, but less restrictive than, *transitive reduction* [4] is used. As Bang-Jensen and Gutin [4] describe, a transitive reduction of a directed graph (digraph) D is a spanning subdigraph H of D with no *transitively irrelevant* arcs, and it is called *minimum equivalent subdigraph*. In transitive reduction, "reachability" between nodes is not affected as only superfluous arcs are removed [41]. The minimum equivalent subdigraph of an acyclic digraph can be found in polynomial time and is unique.

However, in this instance, another algorithm that reduces the number of arcs further is used so that it is less restrictive in maintaining the reachability condition. A simplified visualization of this procedure is presented in Fig. 1 and is mathematically outlined here:

1. Identify the set of all universities which are nondominated; this set will be called the set of "Level 1" universities;
2. Add a dummy vertex v_d, which would correspond to a hypothetical nondominated university by all universities in the set (the Level 0 or "dream university"), and draw an arc from v_d to each of the universities in Level 1 (Fig. 1b);
3. The level of a university (represented by a vertex v_i) is then equal to the number of arcs that need to be traversed in the longest directed path from the "dream university" (vertex v_d) to v_i;
4. For each arc $a_{xy} \in A$ if $|Level(x) - Level(y)| > 1$, then $A = A - \{a_{xy}\}$ (see, for instance, the bold arcs in Fig. 1c are deleted from the DAG Fig. 1d).

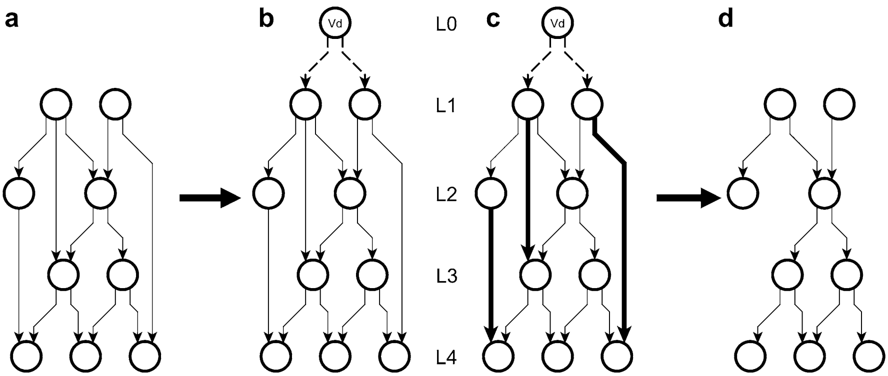

Fig. 1 **Construction of the dominance graph**. Each vertex represents a university, and there is an arc from each pair of universities (x, y) whenever x dominates y, according to the dominance definition given in the text. This method starts by first identifying the set of universities that are not dominated by any other university in the set. To illustrate on the algorithm, a set of figures are produced. Figure **(a)** shows the initial status. By assigning the nondominated set of universities to a top level, it would be possible to identify levels for all the other universities in the set. Figures **(b)**–**(d)** illustrate on the procedure to compute this and the resulting reduced graph as some arcs are removed. In **(b)** a dummy vertex v_d is added, which corresponds to a hypothetical "dream university" which is nondominated, which would be at "Level 0." From the dummy vertex to each of the nondominated universities, an arc is added (as shown in **(b)**). Then a level of a university is recursively defined as the maximum number of arcs that need to be transversed from v_d to it. Figure **(c)** shows arcs that connect universities for which the difference levels are more than one. These arcs are shown in boldface. Since visualizing such a dense directed graph would be unclear, these are removed as it would not affect the level of any given university. As a result, a reduced DAG is produced as shown in **(d)**, and through visualization it is shown how its results now uncover the underlying layer structure of **(a)**

The resulting graph from this process has the same hierarchical properties as the original one. Based on this final reduced graph, university x *"closely dominates"* university y if $a_{xy} \in A$ after the reduction.

This heuristic ranking methodology in terms of levels comes from a clear algorithmic procedure and is nonparametric, and it does not require an ad hoc definition of weights to be applied to each attribute. It is based on established grounds in multi-objective optimization and clearly reflects all pairwise comparable dominance relationships in the data. Furthermore, this method accepts numerical as well as categorical attributes allowing the inclusion of more variables in ranking activities.

Following the above process, in order to investigate "global" dominance relationships, the number of institutions that each university is transitively dominated by in the reduced graph will be calculated. This will provide an overall picture of where each institution is placed in comparison to all institutions included in the set. As an extra decision-making tool, it will provide institution leaders with the necessary information to compare and benchmark against other similar institutions. Examples of this are provided in section "Results".

Symbolic Regression Analysis to Predict Levels Using All Variables

In order to go one step further and investigate which variables are important in terms of "predicting" which level (rank) a university is going to be a part of, symbolic regression analysis is used in this chapter. By doing this, it clarifies whether the results found are consistent when using variables of each year for six consecutive iterations of the symbolic regression analysis. Symbolic regression is a data-driven method to find a structure in data. Unlike linear regression methods, symbolic regression not only finds the best values for a set of coefficients, it also finds the structure of the model that best fits the target variable [57] (including but not necessarily limited to linear models). In order to do this, a powerful software named *Eureqa* [54] is used which is based on evolutionary computation techniques to search for the best model. Eureqa runs an evolutionary search procedure to find the solution that fits the data best with the lowest possible level of complexity as is consistent with other symbolic regression methods [62].

In Eureqa, the "best models" are those that are observed in a Pareto optimality curve which imply a trade-off between their complexity and their fit. Complexity meaning the number of functions and "building blocks" used by *Eureqa* to fit a model to the target variable. The user selects a fitness function (for instance, absolute error or mean squared error) that guides Eureqa in selecting the best models. Users also have the option to select their preferred "building blocks" (for instance, arithmetic operations like multiplication, subtraction, and addition or the introduction of a constant). In a previous publication, the authors of Ref. [64] have shown the usefulness of symbolic regression and *Eureqa* in finding "functional constructs" from online consumer behavior data. Furthermore, the data-driven nature of symbolic regression is suitable to the context of this study as the aim is to make inferences on the data based on the information present in the data alone without a priori parameters or attribute weights.

In this study in particular, the aim is to find those variables that are of importance when "predicting" which level an institution is in as well as finding out whether the assignment to levels of all universities can be consistently predicted with variables from each of the years. To do this, the "level" is set as the target variable in *Eureqa*, while it tries to fit a model to predict between Levels 1–11. The level ranking dataset used for this procedure is the ranking obtain from running the dominance graph on the whole dataset, i.e., years 2007–2012. Following this, six searches are conducted in *Eureqa* in which every search uses only one year of data. The reason is to find out whether the models are consistent in predicting one outcome of the dominance graph using variables from several years. The variables in the dataset that are most frequently used in the models are highlighted, and these are identified as the key variables in predicting "level membership." Furthermore, the best simple linear function found by *Eureqa* is used for further analysis which is consistent with a previous publication using this software [64]. In this manner it is possible to inspect the variables that are found to predict the target variable, in this case, ranking level in detail.

In this study, the following "building blocks" were selected for the *Eureqa* analysis, the use of a "constant," "integer constant," "input variable," "addition," "subtraction," and "multiplication." For all of the six years, the six searches are run two times, once with the error metric as *R-squared goodness of fit* and once with *squared error Akaike information criterion* [AIC]. The *squared error* with AIC is selected as AIC provides a means for model selection. AIC deals with the *goodness of fit* of the model and the complexity of the model which is in line with the other selection criteria that are used based on the Pareto optimality curve.

Results

The results based on the construction of the directed dominance graphs are presented here. The total dataset for the years of 2007–2012 was analyzed and split into two datasets representing the periods 2007–2009 and 2010–2012. In Figs. 2 and 3 the hierarchical layout of the graph created for the three-year periods of 2007–2009 and 2010–2012, respectively, can be seen.

Resulting from the ranking procedure, as outlined in the methodology, the graph of 2007–2009 has 12 levels with a different number of universities in each level in the first period. In the second period, the graph has 13 levels, with Level 13 only containing one university (University of Jyvaskyla, Finland). Furthermore, colors are used to highlight the correlation with the Shanghai Jiao Tong University study. Red corresponds to those institutions that have been considered at the top 10 according to the Shanghai Jiao Tong University study (in the last year included) with the remaining top 50 in orange, and the remaining top 100 are colored in green. Also included in this section are the results of the calculation of transitive dominance of institutions, the symbolic regression analysis testing, the volatility of ranking over a longer period of time, and the removal of the attribute Alumni as well as the attribute PCP (*Size*) in the ranking method and the effects of the removal of each of these attributes on the outcome. In the representation of results, various institutions are highlighted as examples in order to communicate the findings of this study.

University Ranking Results 2007–2009

When looking at Level 1 in Fig. 2, some information that is clearly revealed by the method becomes apparent. The "Level 1" universities correspond to those which are not dominated by any other university in terms of the attributes considered in the method. In this graph, these are Harvard University and the California Institute of Technology (Caltech). While Harvard closely dominates several others, Caltech does not closely dominate any other institution of Level 2. Level 2 institutions are Stanford, Columbia University, the University of Tokyo, the University of California at Los Angeles, the University of Michigan at Ann Arbor, the University of Pennsylvania, the University of Washington, the University of California at

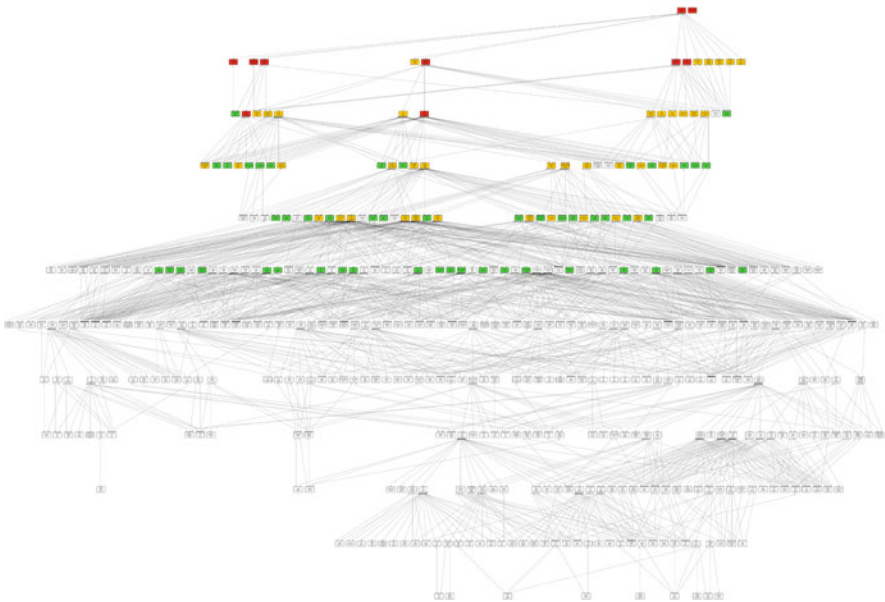

Fig. 2 The ranking of 444 world universities according to our proposed methodology using the same raw data provided by the Institute of Higher Education, Shanghai Jiao Tong University, for the years 2007, 2008, and 2009. Universities are arranged in *levels*, and a university is in a level if there exists another university that *closely dominates* it and is in the immediately higher level (the mathematical definition of this concept is outlined in the Methods Section). This graph provides important information for decision-making. In order to improve the overall ranking level, the university strategic decision-makers should pay attention to the best effective way of reaching the next level by improving in those attributes that would allow it to rank in the next level in the hierarchy. In addition, the university should also closely monitor the set of universities in the inferior level as they are the in direct competition for a position at the same level in the hierarchy. For instance, Yale University and Cornell University are two Level 3 universities that are both closely dominated by University of California at Berkeley. At the same time, these two institutions have a large number of institutions that they closely dominate at Level 4 (NB: A high-resolution version of this image can be found in the Supplementary material)

Berkeley, the University of Toronto, the University of Cambridge, Massachusetts Institute of Technology, and Princeton University.

The reason for Caltech's position in Level 1 can be explained not by Caltech's total productivity but rather its productivity regarding its size. Here it is noted that instead of normalizing raw data on the institution's performance by the number of full-time academics (or their equivalent full-time aggregated data), the Institute of Higher Education, Shanghai Jiao Tong University proposed the addition of an attribute called *"Academic performance with respect to the size of an institution"* or "Performance Per Capita" (PCP). It is important to remark that Caltech is a special case in terms of size. As pointed out by Baty in early 2014 [5], Caltech may be called not just "small," but *"tiny"* with its 300 professorial faculty, about 600 research scholars, and, at the last count, only 1,204 graduate students and just

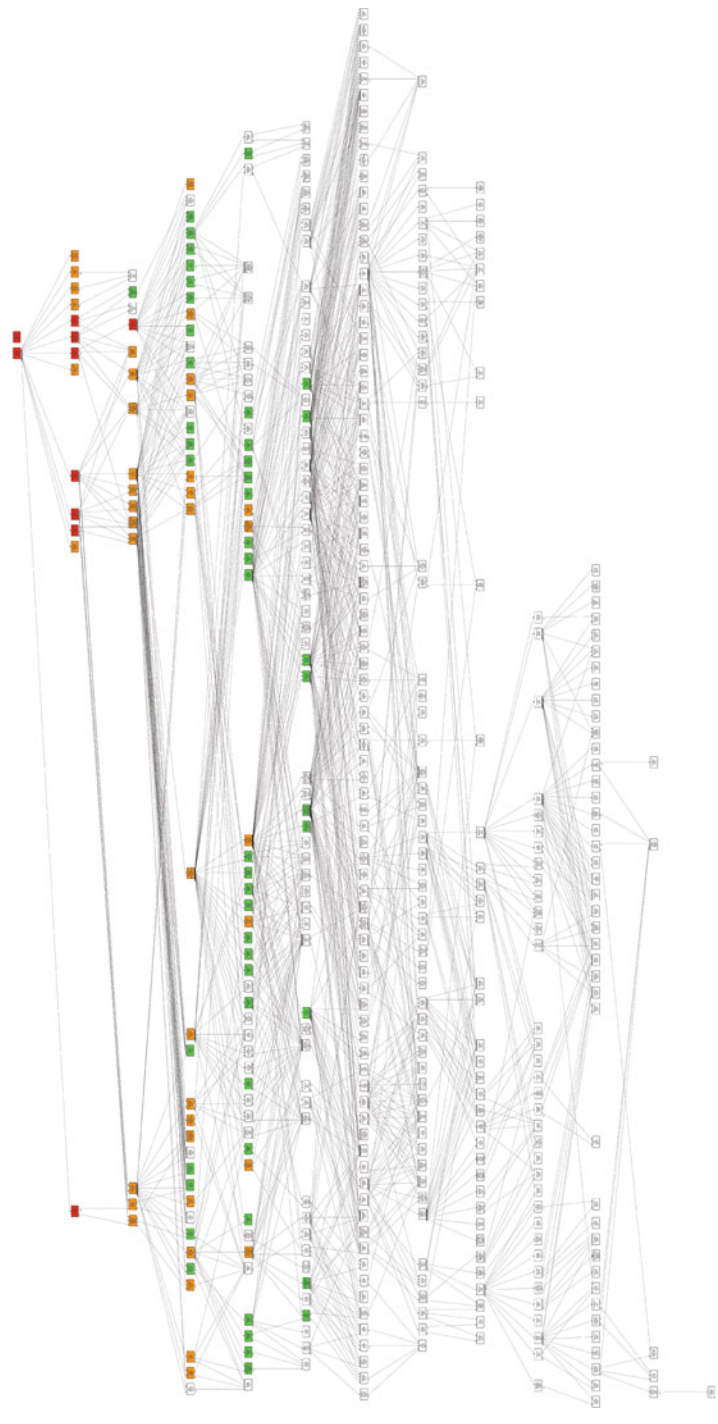

Fig. 3 (Continued)

977 undergraduates. This translates to an almost 3:1 student to faculty ratio. As a result of the introduction of the “Performance Per Capita” (PCP) attribute, which relates to the size of the institution in the ranking method, Caltech (with its “tiny” size) is “singled out” at the top due to its maximum value of this attribute without any close domination of Level 2 institutions. This reflects the consensus that the lack of normalization of the other attributes would bias ranking systems to benefit larger institutions. For instance, Rockefeller University is another small-sized institution that is very productive and is at Level 3, closely dominated by the Massachusetts Institute of Technology at Level 2.

Other Level 3 institutions include the Ecole Normale Superioure of Paris, the University of Chicago, Cornell University, Yale University, the University of Oxford, the University of California of San Diego, Kyoto University, Duke University, John Hopkins University, the University of Minnesota at Twin Cities, the University of Wisconsin at Madison, the University of Sao Paulo, and the University of Pittsburg. The University of Sao Paulo (Brazil) consolidates its position as a world Level 3 institution due to its relatively large SCI performance score.

At Level 4, the international mix of institutions is more clear. Level 4 includes the Hebrew University of Jerusalem (Israel), two German universities (the Technical University Munich and the University of Munich), three UK institutions (the Imperial College of Science, Technology, and Medicine, London School of Hygiene and Tropical Medicine, and the University College London), three from France (Pierre and Marie Curie University Paris, the University of Paris-Sud, and the University of Montpellier), the University of Oslo (Norway), the University of Basel (Switzerland), Moscow State University (Russia), the University of British Columbia (Canada), Osaka University (Japan), and a large group of USA-based universities, Carnegie Mellon University, the University of Colorado at Boulder, the

Fig. 3 The ranking of 444 world universities according to our proposed methodology using the same raw data provided by the Institute of Higher Education, Shanghai Jiao Tong University, for the years 2010, 2011, and 2012. The California Institute of Technology and Harvard University continue to be the single institutions at Level 1. At Level 2, there is almost the same group of American institutions (and The Universities of Tokyo and Cambridge). However, the University of Pennsylvania now is at Level 3, and John Hopkins University and the University of Oxford now climb a level and now are at Level 2. If a single city of interest is to be highlighted, the universities in Hong Kong show a clear upward trend with the City University of Hong Kong climbing (climbing from Level 10 to Level 7), the Chinese University of Hong Kong and the University of Hong Kong (both raised from Level 8 to Level 6), and the Hong Kong Polytechnic University (from Level 10 to Level 8). Other Asian institutions raised three levels (Sun Yat-sen University and Hanyang University, from a Level 11 to Level 8). In Europe the remarkable uphill move of the Italy’s Scuola Normale Superiore di Pisa that raised from Level 6 to Level 3 can be noted, as well as Sweden’s Stockholm School of Economics (from Level 7 to Level 4) and Austria’s Medical University of Innsbruck that from the bottom Level 12 is now at Level 7. However, over the three-year subsequent period, only 10% of the institutions raised two or more levels (and only 4.05% decreased it by a similar gap) indicating that as a metric is less volatile than other metrics to evaluate institutional performance (NB: A high-resolution version of this image can be found in the Supplementary material)

University of California San Francisco, Pennsylvania State University – University Park, the University of Illinois at Urbana-Champaign, the University of Texas Southwestern Medical Center at Dallas, Northwestern University, the University of California Davis, The Ohio State University Columbus, Case Western Reserve University, the University of Florida, Washington University in St. Louis, and the University of Rochester.

Lastly, the Ecole Polytechnique Federale de Lausanne (EPFL) Institute in Switzerland is also situated on Level 4. This institution is highlighted because Ioannidis et al. in [24] have pointed out how the EPFL of Lausanne was a missing institution in the top lists of Shanghai Jiao Tong University ranking system in previous years, yet the methodology in this chapter has the EPFL institution in a relatively high position. The EPFL is located at Level 4 as shown in Fig. 2. Furthermore, as is to be expected, as you move down the levels further, the number of institutions in each level increases, and the variety of origins becomes more apparent which can be examined in Fig. 2. A full presentation of institutions at all remaining levels can be found in Fig. 2.

Transitive Dominance Example Results

As stated, the number of institutions that each university is transitively dominated by and which ones it dominates has been computed, for instance, looking at the three UK-based institutions at Level 4, the Imperial College of Science, Technology, and Medicine, London School of Hygiene and Tropical Medicine, and the University College London. The Imperial College is transitively dominated by only seven universities in the world, while it transitively dominates 337 institutions. This is an impressive number for a Level 4 university, very close to the 346 institutions dominated by Caltech at Level 1. The University College London (UCL) numbers are equally impressive with only five institutions that transitively dominate it and with 377 transitively dominated by UCL. In contrast, the London School of Hygiene and Tropical Medicine is transitively dominated by only 12 institutions (consistent with the overall trend of expected dominance for an institution at this high level), but it does not dominate any other institution.

The same numbers of the three French institutions at Level 4 are Pierre and Marie Curie University Paris (9 and 209), the University of Paris-Sud (9 and 117), and the University of Montpellier 2 (13 and 45). This analysis provides some clarity on the peculiarities of some small-sized but intensively research-oriented institutions.

Sensitivity Analysis of Mobility over the Period 2010–2012

Research policy makers can intuitively evaluate the chances that a university can climb the level structure by way of improving in different attributes. A university can climb up one level only if it improves on those categories in which it is being closely dominated by other institutions (given that those institutions do not move

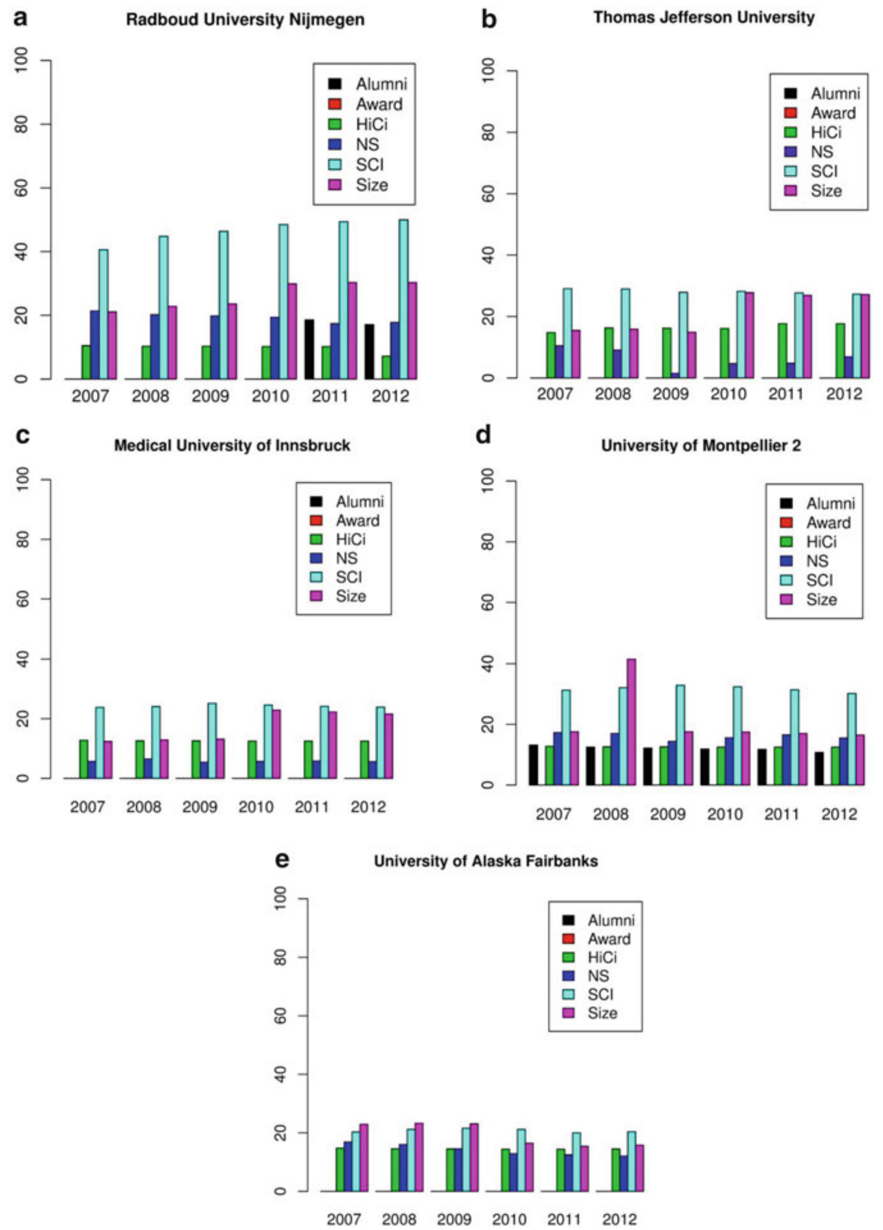

Fig. 4 (Continued)

themselves). The inbound degree and the "weight" of each arc implicitly convey how likely it is for a university to improve its level. It is intuitive that the lower the inbound degree and the lower the weights, the easier it is for a university to climb levels up in the overall ranking.

There is a clear linear correlation trend between changes in levels and changes in the transitive dominance of a given university. In order to inspect this, a comparison is made between the change in level position of the 2010–2012 dominance graph and the 2007–2009 dominance graph. Firstly, several universities are highlighted as examples of level changes, followed by universities' changes in level over these two periods when the attribute PCP is removed from the dominance graph computation. This will show those changes that occur based on only the other attributes that remain.

Figure 4 shows five universities that provide different examples of changes in levels. Firstly, in Fig. 4a, the Netherland's Radboud University Nijmegen is shown. In the Figure it is noticeable that the attribute "Alumni" is nonexistent in the years 2007–2010 and appears for the years 2011–2012. For the case of the Radboud University Nijmegen, this steep increase is due to the fact that in 2010, two researchers affiliated to the University obtained the Nobel Prize in Physics for their research in the properties of graphene [43]. Examining these types of changes further, results show that the Radboud University Nijmegen shows an impressive improvement (from 58 institutions dominating it to only 12). Next in Fig. 4b, the USA-based Thomas Jefferson University attributes are shown which explain its level improvement to Level 6 from a previous Level 10 position and has only 41 universities dominating it from a previous 162 total. The Figure shows that between the period 2007–2009 and 2010–2012, the Thomas Jefferson University increased significantly in the attribute related to size (PCP). The Medical University of Innsbruck that was at the lowest level in 2007–2009 (Level 12) jumped to Level 7 in 2010–2012 also experienced the largest change in transitive dominance (from 222 to 88) and is shown in Fig. 4c. This is a change of approximately 60% in the number of institutions that dominate it. In this figure it shows that the Medical University of Innsbruck has a steep increase in the value for the attribute related to size. As

◀

Fig. 4 **Attribute values of universities that have changed levels over time –** Figure **(a)** shows Radboud University which has climbed levels due to their increase in Alumni score. In figure **(b)**, Thomas Jefferson University provides an example of a university that has improved its level position due to an increase in Performance Per Capita (PCP), likely due to the institution changing in size. The Medical University of Innsbruck also provides an interesting example in figure **(c)** as it has the largest climb in level (from Level 12 to Level 7). It is possible to see for this university that all the categories are kept mostly the same, with the exception of category PCP, related to size. Figure **(d)** shows the university with the largest change in its level, University of Montpellier 2, which dropped from Level 4 to Level 8 when comparing the two periods that are investigated in this study. The profile of the university shows an unusual value for the PCP category in year 2008. This is probably due to an error in the data collected or published. Finally, in figure **(e)**, the University of Alaska Fairbanks drops from Level 7 to 10 which is explained by the drop in the category N&S, as well as the drop in PCP (Size) stated, this attribute measures “Per Capita Performance” (PCP) in terms of research. Therefore, it could be that either the University reduced in size at this point in time or that it has significantly increased their research output with the same institutional size or even that some part of its research output was not previously included.

Furthermore, Fig. 4d shows the French University of Montpellier 2 and its peculiar values for the attribute “Size” (PCP). When comparing the two periods of time, the University of Montpellier 2 experiences a large drop in their level position from Level 4 to Level 8. In the figure it is evident that the University of Montpellier 2 had a steep decline in their score for the attribute “Size” (PCP). It may be argued that this could be due to an abnormality in one of the values of “PCP” (for the year 2008) which is conspicuously high. As a consequence, this may have affected the position of this university in the level for years 2010–2012. Finally, Fig. 4e shows the University of Alaska Fairbanks. This university is also an example of a university falling in its level position. The University of Alaska at Fairbanks is now at Level 10 from a previous position at Level 7. In the figure it can be seen that this drop is explained by the decrease in the attribute of N&S as well as a large decline in PCP.

Considering that many universities’ drop in level can be attributed to their change in PCP, the results of the two periods without the PCP variable are compared. This will show those universities that still change in level position without considering their Performance Per Capita and may shed light on which other attributes are important to level position changes. Fig. 5 shows four universities which provide examples of this. In Fig. 5a, the UK-based University of Bath is shown. The University of Bath declined in its position over the years due to a decrease in the value for N&S attribute. The USA-based Northeastern University and the Australian University of Tasmania are shown in Fig. 5b, c, respectively, and show the reason for their level improvement. For both of these universities, their level improvement can be attributed to their increase in value for the N&S attribute in the new three-year period. This means that it is likely that each of these institutions shifted resources, and academics allocated their time differently in order to publish more in the journals Nature and Science in the second period (2010–2012) than in the first period (2007–2009). Lastly, Fig. 5d shows the City University of Hong Kong which experienced a drop in their position due to the decline in citations in N&S. Interestingly, although their value for “HiCi” improves in the newest three-year period, the drop in N&S is enough to shift this university’s level position.

A complete list of the results of universities’ mobility over the two time periods, for those universities that fell or increased more than two levels, is shown in Table 2.

Dominance Graph Computation of 2007–2012 with Symbolic Regression Analysis

After the periods 2007–2009 and 2010–2012 were examined separately, the results of the dominance graph for the whole period are examined. The resulting dominance graph is displayed in Fig. 6.

Examining the results of universities’ position in the dominance graph over a total of 6 years allows the further investigation of the implications for institutions.

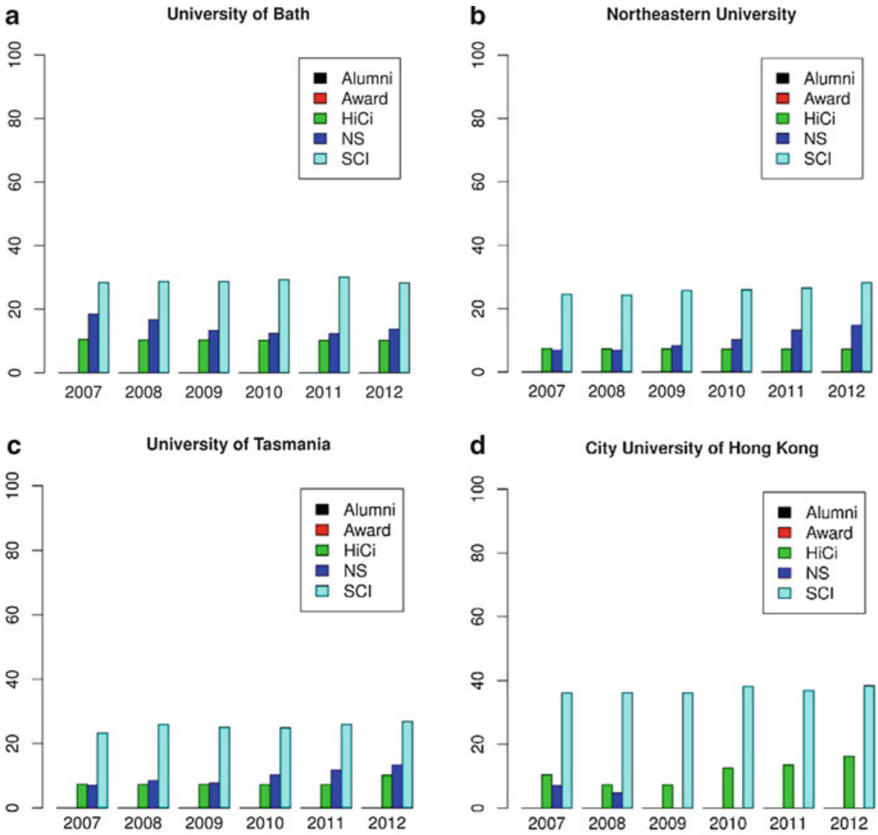

Fig. 5 Examples of universities that still moved levels in between the two periods of time when Performance Per Capita (PCP) was moved – This figure shows four universities that dropped or improved in their level position in the dominance graphs of 2007–2009 and 2010–2012 without PCP included. Figure **(a)** shows the University of Bath, which drops two levels between 2007–2009 and 2010–2012 due to their decrease in the value for the attribute N&S. Figure **(b)** shows Northeastern University which is the university that shows the largest improvement in level position in this comparison. As can be seen in this figure, their improvement can be attributed to their high values for N&S and SCI. Next, in figure **(c)**, the University of Tasmania shows that their rise from Level 16 to 13 is mainly due to their increase in the category N&S. Finally, figure **(d)**, the City University of Hong Kong jumps from Level 13 to 10 although they have a value of zero for the attribute N&S after 2009. The figure shows their level improvement is solely due to the increase in Highly Cited work HiCi

This is because this graph compiles all the scores for all attributes for each year. With more information available in one ranking outcome like this, more inferences can be made for institutions, strategic planning activities, and research policy making. As stated in section "Materials and Methods", symbolic regression analysis is used on the 2007–2012 ranking results to find those variables that are important in predicting a universities' rank as well as test for consistencies using data from

Table 2 Universities that change more than two levels in the Pareto dominance graph in the two periods of years considered

University	Level		Change
	2007–2009	2010–2012	
Medical University of Innsbruck	12	7	−5
Sao Paulo State University	11	7	−4
Thomas Jefferson University	10	6	−4
City University of Hong Kong	10	7	−3
Hanyang University	11	8	−3
Northeastern University	12	9	−3
Scuola Normale Superiore di Pisa	6	3	−3
Stockholm School of Economics	7	4	−3
Sun Yat-sen University	11	8	−3
University of Alaska Fairbanks	7	10	3
University of Montpellier 2	4	8	4

each year to predict the ranking of the 2007–2012 outcome. Using *Eureqa*, the aim is to find a linear function using the existing variables in the dataset to predict the level each university is a "member" of. Two separate error metrics are used to optimize the R^2 goodness of fit (GoF) and the squared error [AIC]. In each experiment the objective was to fit a model to predict the levels of the dominance graph shown in Fig. 6 using, in turn, the variables from each of the years 2007–2012. Results for the experiments optimizing R^2 GoF are shown in Table 3. Results optimizing the squared error [AIC] are shown in Table 4. As can be seen in these tables, all models contain the same variables, Alumni, PUB (research output), and PCP (related to size), for one exception which includes N&S (publications in Nature and Science) instead of PUB. However, it is noted that both PUB and N&S relate to a universities' research output and could therefore be seen as interchangeable as different institutions have higher research outputs in varying disciplines.

Furthermore, all models have highly similar coefficients. All constants at the start of each model range between 9.59 and 10.91 followed by highly similar coefficient attached to the Alumni attribute (ranged between 0.02 and 0.04). Following this, all models, except for that one using 2011 data and the Square Error [AIC], contain the attribute PUB with a coefficient ranging between 0.05 and 0.06. For the exception, N&S is included with a coefficient of also 0.05. This shows that for almost all models, PUB has a greater weighting in predicting universities' levels than the Alumni attribute does. Finally, for all models other than the 2011 model in Table 4, PCP is the last included attribute with the heaviest weighted coefficient between 0.09 and 0.10. Again, the exception is the model using squared error [AIC] using 2011 data which includes PUB as its last variable with a coefficient of 0.06 (which is similar to the coefficient attached to PUB for all other models). Besides this one exception, these models show a high level of

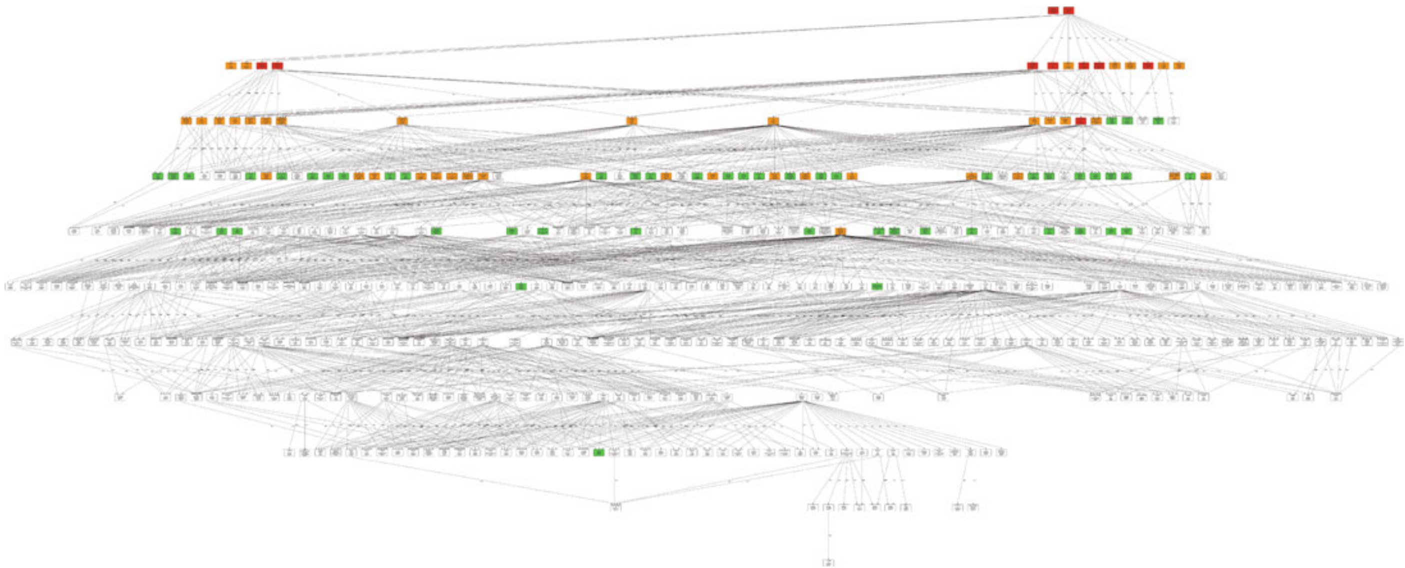

Fig. 6 **Results of the dominance graph for the whole period 2007–2012.** This graph contains a total of 11 levels, and consistent to the other results, Harvard University is still in Level 1 and directly dominates multiple universities in Level 2. The California Institute of Technology is again the only other institution on Level 1 but does not directly dominate and institutions in Level 2. Again, the coloring is consistent to the other dominance graph figures to highlight the ARWU ranking (NB: A high resolution quality of this image is available in Supplementary material)

Table 3 Results of the symbolic regression analysis predicting “level membership” or position. In this table the best linear models found using the R-squared goodness-of-fit measure are presented including the respective error metric. The experiment was run six times to include variables from each of the years separately to find consistencies in the variables used by *Eureqa*. As can be seen, all models are very similar; include the same three variables, Alumni, PUB (related to number of publications), and PCP (related to size); and even have almost identical coefficients

Year of variables used	Best linear model for level prediction	R^2 GoF
2007	Level = 10.40 − 0.02(Alumni) − 0.05(PUB) − 0.10(PCP)	0.71
2008	Level = 10.39 − 0.03(Alumni) − 0.05(PUB) − 0.09(PCP)	0.69
2009	Level = 10.41 − 0.02(Alumni) − 0.06(PUB) − 0.09(PCP)	0.71
2010	Level = 10.91 − 0.02(Alumni) − 0.06(PUB) − 0.10(PCP)	0.71
2011	Level = 10.90 − 0.02(Alumni) − 0.06(PUB) − 0.10(PCP)	0.71
2012	Level = 10.87 − 0.02(Alumni) − 0.06(PUB) − 0.10(PCP)	0.71

Table 4 Results of the symbolic regression analysis predicting “level membership.” In this table the best linear models found using the squared error [AIC] measure are presented including the respective error metric. As in Table 3, the experiment was run six times to include variables from each of the years separately to find consistencies in the variables used by *Eureqa*

Year of variables used	Best linear model for level prediction	Mean squared error
2007	Level = 10.56 − 0.02(Alumni) − 0.05(PUB) − 0.10(PCP)	1.04
2008	Level = 10.40 − 0.03(Alumni) − 0.05(PUB) − 0.09(PCP)	1.11
2009	Level = 10.75 − 0.02(Alumni) − 0.06(PUB) − 0.10(PCP)	1.03
2010	Level = 10.87 − 0.03(Alumni) − 0.06(PUB) − 0.10(PCP)	1.04
2011	Level = 9.59 − 0.04(Alumni) − 0.05(N&S) − 0.06(PUB)	1.21
2012	Level = 10.76 − 0.03(Alumni) − 0.06(PUB) − 0.10(PCP)	1.05

consistency across which variables are used to predict “level membership” for universities. These results indicate that PCP (size) has a big impact on predicting which level a university is part of in the dominance graph of the ARWU dataset. Furthermore, it can be observed that PUB has a stronger impact on determining which level a university is on than Alumni and that these three attributes combined predict the levels of the 2007–2012 dominance graph to reasonable error values (as shown in Tables 3 and 4). Finally, these symbolic regression results could assist a university in determining strategies for improvement in the ARWU ranking as they provide the strongest impacting attributes on which level a university is on.

To further illustrate the usefulness of the proposed ranking method in this chapter in detail, various examples are outlined from the 2007–2012 dominance graph. The universities selected to provide case examples are the University of Copenhagen, the University of Amsterdam, and the Australian National University (ANU) as these institutions provide varying interesting cases.

Fig. 7 The position of the University of Copenhagen at Level 4 in the dominance graph of the period 2007–2012. The University of Copenhagen provides an interesting example as it is only directly dominated by one university in Level 3, Yale, and it dominates a total of 30 universities directly

Case Example of the University of Copenhagen

In the total period of 2007–2012, the University of Copenhagen was positioned on Level 4 of the dominance graph. As shown in Fig. 7, the University of Copenhagen is only closely dominated by one university, Yale, while it closely dominates 30 other institutions in Level 5. The fact that only Yale directly dominates the University of Copenhagen in our ranking result is a satisfactory achievement for the University of Copenhagen as this means the "inbound degree" of arcs for Copenhagen is low. However, it must be outlined that as the weight of the arc between Yale and Copenhagen equals to 36, it means that Yale dominates Copenhagen in every attribute for every year ($6 \times 6 = 36$). This shows that the weight of each arc is important in the dominance graph and provides information to the institutions wishing to directly benchmark with other institutions having very similar, though superior, profiles.

Case Example of the University of Amsterdam

In the total period of 2007–2012, the University of Amsterdam (UvA) was positioned on Level 5 of the dominance graph. It is one of the 30 universities that is closely dominated by the University of Copenhagen. Those universities that dominate the UvA and those that the UvA closely dominates are shown in Fig. 8 and create a cone-like shape that the UvA can analyze further for benchmarking purposes. As can be seen in the figure, the UvA is only closely dominated by Northwestern University, the University of Copenhagen, and the University of Illinois at Urbana-Champaign. The University of Amsterdam closely dominates nine universities at Level 6. Five of these universities are from Asia, Fudan University in China, Nanyang Technological University in Singapore, the University of Hong Kong, and the City University of Hong Kong. One such university is from Brazil, State University of Campinas; two universities from Europe, University of Erlangen-Nuremberg in Germany and the Swedish University of Agricultural Sciences; and, finally, one university from Israel, Yeshiva University.

Analyzing the relationship of UvA and the universities it is closely dominated by provides higher education decision-makers and research policy makers with further information about where to exert their resources more heavily. For instance, in the example of the UvA, it is shown how "close" UvA is to those universities that dominate it and possible areas of concentration for UvA to gradually improve its rank according to this system. For this, the scores of attributes only for the year 2012 are used as this is the most recent year in this dataset and therefore provide the most up-to-date answers. The attribute with the smallest difference in score for UvA and one of the universities is dominated by is "PCP" (Performance Per Capita). The UvA has a score in 2012 of 25.8, while the Northwestern University has a score of 26.4 making it only a 0.6 difference in score. This means that if the UvA improves in this item by just a mere 0.6 of a point score, it can change the domination status of one of the three institutions at a higher level that closely dominate it.

Furthermore, the University of Illinois at Urbana-Champaign has a score of 27.8 for PCP meaning that UvA is only 2% points lower. The University of Copenhagen

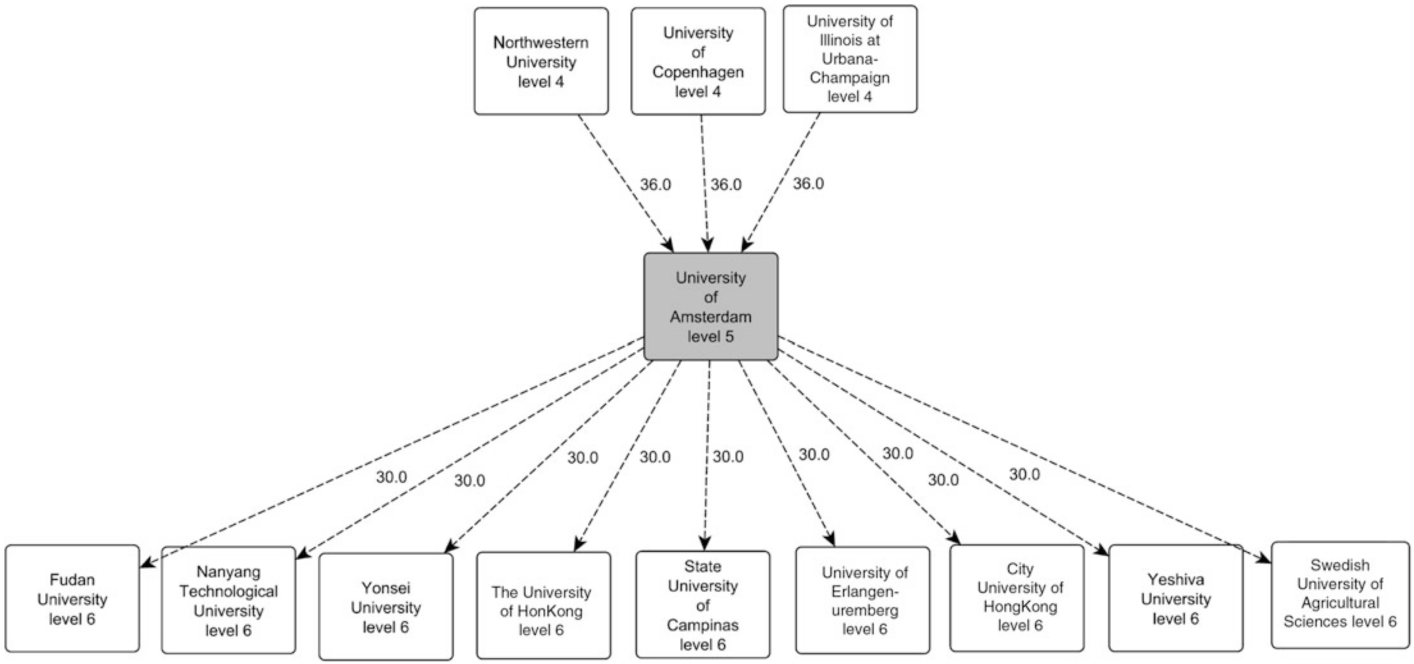

Fig. 8 The position of the University of Amsterdam at Level 5 in the dominance graph of the period 2007–2012. It shows that the University of Amsterdam is directly dominated by three universities at Level 4, Northwestern University, the University of Copenhagen, and the University of Illinois at Urbana-Champaign. In turn, the University of Amsterdam dominates nine other universities directly in Level 6 as shown in the figure

has a score of 32.3 for PCP making it 6.5 points higher than UvA. The second closest attribute score for UvA and its dominating universities is in "PUB." UvA's score in this attribute in 2012 is 52.8 while the University of Illinois at Urbana-Champaign has a score of 56.1 meaning there is only a 3.3 point difference. Northwestern University has a score of 58.1 (5.3 point difference with UvA) and the University of Copenhagen has a score of 58.6 (5.8 point difference with UvA). These results tell us that the UvA is closest to its dominating institutions in these attributes. This can inform management at UvA to focus attention and resources on increasing publications in certain journals and in doing so improve their Performance Per Capita (PCP) instead of investing heavily in other attributes in which the differences are pronounced.

Case Example of the Australian National University

In the analysis using the total period of 2007–2012, the Australian National University (ANU) was positioned on Level 4 of the dominance graph which is the same level as the University of Copenhagen (see Fig. 9). ANU is closely dominated by six universities at Level 3, while it, in turn, closely dominates five universities at Level 5. The universities that dominate ANU are all from the USA or the UK, University of California San Diego; Yale University; University College London;

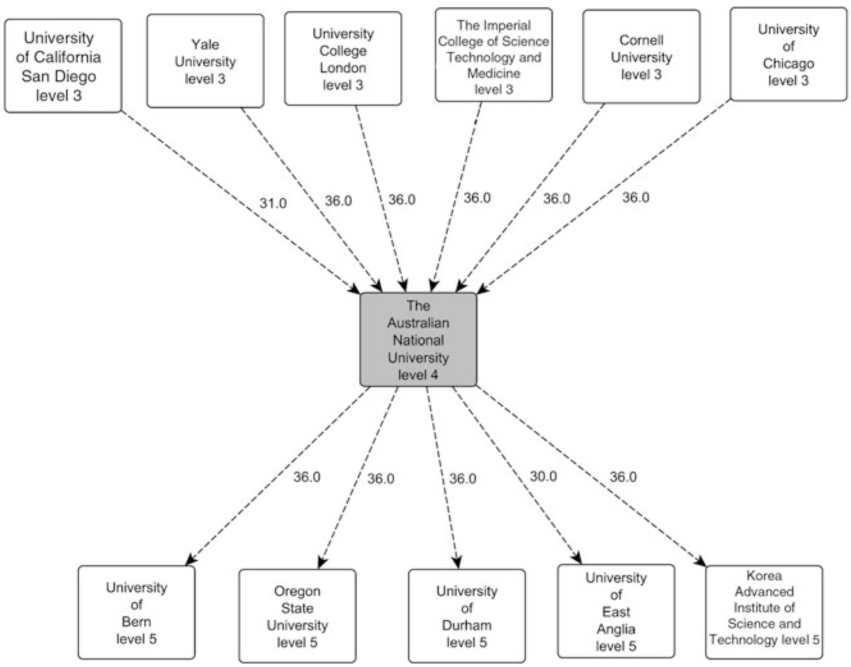

Fig. 9 The position of the National University of Australia at Level 4 in the dominance graph of the period 2007–2012. It is closely dominated by six universities at Level 3, while it, in turn, closely dominates five universities at Level 5

the Imperial College of Science, Technology, and Medicine; Cornell University; and the University of Chicago. The universities that ANU closely dominates are a more international mix, the University of Bern in Switzerland, Oregon State University from the USA, the University of Durham and the University of East Anglia in the UK, and Korea Advanced Institute of Science and Technology.

ANU is taken as an example of how to investigate the relationship with those universities a given institution closely dominates. In the case of ANU, there are five. In this scenario it is important to investigate which universities would be close in certain attributes or in some cases almost equal. Once the university of interest is no longer better in all attributes, it will no longer closely dominate those universities. Again, only the scores from 2012 will be investigated to provide a scenario as up to date as possible. In the case of ANU, three of the closest scores are in the attribute "Alumni" which relates to the alumni of the institution that obtain a Nobel Prize. In most cases, this is extremely difficult to alter, and a discussion on this attribute is provided in the following section. The next attributes in which universities closely "compete" with ANU are the attributes N&S and PCP.

The closest university in terms of the attribute N&S is the University of Bern followed by Oregon State University. These universities have scores less than 4 points below that of ANU making them competitors for ANU in this system. In terms of PCP, the Korea Advanced Institute of Science and Technology and the University of Bern again come close to ANU. The reason these attributes are outlined rather than Alumni is because these attributes are more in the control of the university than the number of Nobel Prize winners they "produce." For instance, ANU could encourage and enable its researchers to publish articles in Nature and Science rather than other journals in the field. Furthermore, when improving research output in terms of quality and volume without growing in size, it would be likely that Performance Per Capita would increase. These results show us the attributes that ANU needs to focus on in order to keep their competitive advantage and higher position in the dominance graph due to the universities they closely dominate.

The Case of the Alumni Attribute

In the ARWU ranking, the attribute measuring "Alumni," "the total number of the alumni of an institution winning Nobel Prizes and Fields Medals," has been extensively scrutinized and criticized for not measuring actual research or teaching excellence [25, 45]. As Ioannidis et al. [24] state, there is no doubt that research excellence *could* indirectly be measured by the Nobel and Field Medal faculty members working at a given institution. However, there is no justification to assume the existence of any clear correlation with the quality of teaching and research as a whole of the institution. Perhaps, it is only a measure of maturity, sheer size, number of graduates, financial support, and capital investment on a particular discipline (only certain disciplines can give Nobel Awards or Field Medals). In addition, it is unclear why an event with such a low probability of occurrence (very few individuals receive Nobel Prizes or Field Medals) has such a large impact on the activities measured over populations of individuals. Furthermore, Ioannidis et al. have well argued that, in many cases, the affiliation of the Nobel and Field Medals differs at the time they actually conducted the award-winning work and the time that they were awarded the prize [24].

To prove that an attribute in the ranking process may be a spurious one, another type of sensitivity analysis is conducted as part of this chapter's proposed heuristic method. The attribute *Alumni* is eliminated and its effects on the ranking of the universities and their levels over the whole period 2007–2012 are subsequently investigated. It was previously observed that institutions such as the Netherland's Radboud University Nijmegen may have obtained dramatic changes in overall level position due to the attribution of Alumni alone (as can be seen in Fig. 4a shown by the black bar) which provides yet another reason for the comparison of these two outcomes.

According to the definition, the category Alumni represents *"the total number of the alumni of an institution winning Nobel Prizes and Fields Medals. Alumni are defined as those who obtain bachelor, Master's or doctoral degrees from the institution"*. In order to analyze the effect of this category in the ranking analysis, the dominance graph without the Alumni category is recalculated. Thus, each of the 444 universities performance is only observed in the remaining five scores in six consecutive years.

The resulting dominance graph on this dataset has 11 levels which is the same number of levels as the result of 2007–2012 period with all attributes included. This means that any changes in levels by a university is significant and provides useful information. However, here only those universities that increased or dropped by two or more levels are presented for the sake of brevity.

From the 444 universities, 196 universities (44.14%) do not change in level when the attribute Alumni is taken out of the dominance graph algorithm. There are 226 universities (50.9%) that change in only one level and only 21 universities (4.73%) that fall two or three levels. Furthermore, there is only one university (City University of New York City College) that falls four levels, indicating the robustness of this scheme. This points out the irrelevance of the Alumni attribute for the presented heuristic ranking method. This may please those opposed to Alumni being included as a proxy for measuring quality.

However, it is interesting to highlight how the performance of individual institutions may be affected by this choice. Looking at the City University of New York City College, without its impressive legacy of Nobel Prize winners, falls from Level 5 to Level 9. It was clearly in a higher level due to its high performance in the Alumni attribute (with a score of more than 37 in the three years), but the score in the rest of the categories is no higher than 18.

The three universities that fall more than three levels are Eotvos Lorand University in Hungary which fell from Level 7 to Level 10, University of Chile which fell from Level 8 to Level 11, and Saint Petersburg State University from Russia which fell from Level 6 to Level 9. It is clear that these institutions, without their successful score in the Alumni attribute, fall down to lower levels as their scores reflect much

Table 5 Universities that change more than two levels in the Pareto dominance graph in the period 2007–2012 when the attribute Alumni is not considered. There are another 226 universities that drop one level

University	Levels dropped
City University of New York City College	−4
Eotvos Lorand University	−3
University of Chile	−3
Saint Petersburg State University	−3
Case Western Reserve University	−2
University of Nebraska Lincoln	−2
University of Tuebingen	−2
Queen Mary U. of London	−2
Technical University of Berlin	−2
The University of Connecticut Storrs	−2
University of Cape Town	−2
Brigham Young University	−2
Ecole Polytechnique	−2
Technical University Darmstadt	−2
The University of Montana Missoula	−2
University of Oulu	−2
Moscow State University	−2
Complutense University of Madrid	−2
University of the Witwatersrand	−2
University of Warsaw	−2
Istanbul University	−2
Technical University of Braunschweig	−2

lower results in the other categories. It is also interesting to note that the Radboud University Nijmegen in the Netherlands, which, as pointed out, increased in levels over the two separated periods (2007–2009 and 2010–2012), actually falls from Level 5 to Level 6 over the whole period (2007–2012) when the attribute Alumni is not considered. This strengthens the argument that their climb in levels over the six-year period is merely due to their Alumni winning the Nobel prize in Physics rather than a total improvement in "academic excellence" supporting those who argue the superfluous nature of the Alumni attribute in measuring "academic excellence." The results of all universities which dropped or gained two or more levels with the removal of the Alumni attribute are shown in Table 5.

The Case of the Performance Per Capita Attribute (Size)

In the ARWU ranking, the only way in which the "size" of an institution is taken into account is through the only per capita measure: Performance Per Capita (PCP). In the ARWU ranking, PCP is defined by as "*The weighted scores of the above five indicators divided by the number of full-time equivalent academic staff. If the number of academic staff for institutions of a country cannot be obtained,* *the weighted scores of the above five indicators is used.*" [3]. Since this attribute is the only variable in ARWU's ranking method which takes an institution's size into account, it is an interesting image to see the effect of its removal on our methodology.

The sample of 444 universities over the total period of 2007–2012 has been used for the dominance graph algorithm in order to compare its outcome to the result of the 2007–2012 results for all attributes. There are more changes to the outcome when PCP is removed than when Alumni was removed. Firstly, the resulting dominance graph has 12 levels which means that some universities may change in levels due to a total reorganization of the graph. This means that all universities which changed more than two levels are significant; however, this presents a total of 124 universities; therefore, again for the sake of brevity, only those universities which changed in more than three levels are reported here. In these results, only 138 universities (31.08%) did not change a level, 182 universities (40.99%) changed in only one level, 84 universities (18.92%) changed 2 levels, and exactly 40 universities (9%) changed three or more levels.

In the case of deleting the PCP attribute from the method, the most extreme result is the Scuola Normale Superiore di Pisa in Italy, which drops an impressive 8 levels from Level 3 to Level 11. This incredible drop is likely due to its extremely small size in terms of staff and students. The Scuola Normale Superiore (SNS) has only approximately 150 undergraduate students, 120 postgraduates, and only 190 doctoral students as it only takes approximately 60 new students annually through its highly selective entry exam. However, it is important to note that the SNS in Italy is an entirely special case. In order to attend this institution, students sit a rigorous entry exam and must obtain certain levels of grades to remain enrolled in SNS. Furthermore, what makes SNS a special case is that its undergraduate students follow courses at the public university, the University of Pisa (Level 6 in the results without PCP), while living on the SNS campuses. This means that its research academics are able to devote their time to research and that they only have high-caliber students. This explains their impressive result in terms of Performance Per Capita and the incredible drop when PCP is removed from the method.

Furthermore, a small Swiss Institution the Swiss Federal Institute of Technology (EPFL) located in Lausanne has previously been highlighted. Another small Swiss institution the Swiss Federal Institute of Technology Zurich (ETHZ) is highlighted for a different reason. ETHZ was located on Level 3 in the result when all attributes were included in the method; however, with PCP removed, ETHZ fell to Level 4. The removal of the PCP attribute also had a negative effect for EPFL which fell from Level 4 to Level 7. This shows that for many small institutions, the attribute which takes Size into account is important for their position on the ranking levels.

The last small institution that is discussed here provides a particularly interesting case, Princeton University. Between the result for 2007–2012 with all attributes included and the result with PCP removed, Princeton remains on Level 2. In both results, Princeton University is only closely dominated by Harvard. The only change is in the universities Princeton closely dominates as it dominates the Scuola Normale Superiore di Pisa just discussed and Ecole Superieure Paris in the result of all attributes but does not closely dominate any institution when PCP is removed from the method. This is because both these institutions drop in levels when PCP is removed leaving no Level 3 institution closely dominated by Princeton. From this result for Princeton University, it can stated that even though it is a small institution when compared to the likes of Harvard, it "holds its ground" even when the only *per capita* measure is removed unlike the other small institutions that have been discussed.

Discussion

This section elaborates on the findings of the proposed heuristic ranking method and reflects on the contribution of this chapter from a mathematical standpoint as well as a research policy making standpoint which is the application in this chapter to highlight the usefulness of this method. Furthermore, a brief overview of other existing multi-objective ranking methods is provided as a means for comparing the method presented in this chapter. This brief review is then used to highlight several benefits of this chapter's methodology as well as define any future research possibilities to improve the method. Firstly, the two main contributions of this chapter are described in further detail which are a mathematical contribution in terms of a transparent, user-centric heuristic ranking method through the use of a dominance graph and the provision of implications for decision-makers, managers, and research policy makers at educational institutions and governmental offices.

A Transparent and User-Centric Ranking Method

As stated, many authors argue that current ranking systems which include arbitrarily assigned weights and measurement approaches are generally naive, biased, flawed, or a combination of all.

This chapter has attempted to provide a different approach to the ranking of objects with multiple attributes through the use of the global universities ranking example. Needless to say, the methodology is applicable to other types of problems and would allow users of this method to naturally deal with attributes that are numerical and/or ordinal in nature. For example, scores or attributes that have ordinal values in categories could be taken into consideration for this method allowing a much wider adoption of this method for different ranking needs that include a variety of attributes or objects. The aim of discussing particular case examples was to provide an illustration of the user-centric approach of this method which allows alternative ranking outcomes to be investigated according to the user's interests and needs. It is for these reasons that the simple method used in this chapter is easily transferable to other situations.

One of the main benefits of the heuristic ranking method proposed here is that each user with differing interests can be satisfied by selecting which of the attributes must be included in the ranking. As it has been pointed out, the position of several universities changed with the deletion of an attribute. This means that this system allows users to look at the world ranking of universities based on attributes that matter to them and exclude those that do not. Naturally, this would also apply to other ranking and ordering exercises in different situations where users may have varying interests. Such instances could include the ranking of medical institutions for possible medical treatments, companies or organizations for prospective employment, or even the analysis of countries or cities with attributes relating to "livability."

Furthermore, the approach to ranking of global universities in this study provides a more transparent method as it uses raw data rather than accumulated, normalized, or weighted data. As it is the weighting of the data in the ARWU ranking of world universities that concerns a large number of authors [25], it is argued that the proposed heuristic hierarchical method presented in this chapter satisfies a missing need for transparently ranking universities based on raw data available publicly. As it has been explained, although current university ranking methods seem to be flawed and subject to data inaccuracy, scholars and educational institution leaders agree that these activities are "here to stay" [52]. Hence, utilizing a methodology which is transparent and user centric may be more appropriate for the world "need" of global university rankings and other ranking activities.

Implications for Research Policy Makers

As stated before, well-known annual rankings of global universities, such as the ARWU, are often criticized due to their level of volatility [52]. The advantage of the methodology proposed in this chapter is that it organizes global universities in levels based on a dominance graph rather than a "string list." This means that the real nature of slow and steady university growth and improvement is reflected in this method rather than highly volatile changes. As such, this methodological approach correlates well with the subjective assumption that large institutions, like universities, when compared with other institutions of similar size and prestige, do not experience high levels of volatility in terms of their status over periods spanning just a few years. This level-based scheme induced by a dominance graph shows low volatility over consecutive periods of three years and therefore reflects the *real-life* nature of large educational institution growth.

The ability of an educational institution to compare and benchmark itself within the "ladders" of the hierarchy of the presented layers is what actually brings university leaders a clear path for improvement as outlined in the case of the University of Amsterdam in section "Case Example of the University of Amsterdam". Or conversely, a clear image of close competitors in levels below that institution can be examined, as highlighted with the example of the Australian National University in section "Case Example of the Australian National University". In these examples it was easily and clearly identified that these universities' nearest objectives (subset of the top layer that dominate that university) and those attributes they should consider to "protect their standing" (the ones a university closely dominates in the layer immediately below). This knowledge is of considerable value to universities and its research policy makers as it aides strategic decisions regarding the distribution of resources and funding. Although many different approaches to find the optimal allocation of resources by universities exist, for example, such as in [33], since global ranking systems are here to stay, ways of improving on these systems will become more valuable.

Furthermore, it has been found that changes in resource allocation have an impact on the type of activities academics concentrate on [33]. This means that those universities in sections "Case Example of the University of Amsterdam" and "Case Example of the Australian National University", who needed to improve in areas such as publications in Nature and Science, can base their decisions for allocations of resources on numbers that will actually help them in the global standing of universities.

Overview of Existing Multi-objective Ranking Methods

The problem of multicriteria ranking has been active in the decision-makers research community for several years. In most cases, authors aim to produce a total order of the alternatives, or as it has previously been referred to in this chapter, a "string list" of object number one to the bottom ranked object. It is possible to classify the methods presented in two approaches: the first one, and most common, is the use of different ways of aggregating the criteria (features) such that different ways of combining allow to obtained better rankings. Examples of the above can be found in [9, 10, 18, 19, 21, 26, 27, 61, 65, 66]. It is arguable whether a specific way of combining or weighting criteria is better than other. The second approach to solving this problem is by modeling it as a multiobjective optimization problem and to solve it by using, for example, evolutionary algorithms. Examples of the above can be found in [15, 23, 35, 36, 46]. This approach has not been fully exploited, and recent advances in evolutionary algorithms and other techniques to solve multi-objective optimization can be applied. It is also well known that the use of specific knowledge of the problem in the solution leads to good performing methods. In the literature, several applications of domain-specific multicriteria ranking methods can also be found, which incorporate characteristics of the problem at hand in order to combine the different criteria to make the decision. Examples of the above can be found in [11, 12, 31, 38, 42, 44, 48, 51, 53, 55].

Independently of the approach used, all methods aim to produce more reliable rankings and benefit decision-makers. The approach presented in this chapter differs from the ones presented above in that it neither aggregates criteria or produces a total ranking of the alternatives. The method uses multiple criteria (features) in the way they are delivered and only compares values of alternatives into each criteria. This simple method allows the user to scale to several alternatives or objects to be ranked and produces groups or layers of alternatives that are distinguishable from the others, but that between them there is no single alternative that is better than other, according to the criteria considered. In other words, the results of the dominance graph heuristic approach “ranking” provides the user with more information for comparison as the different layers can be compared, as well as the outcomes within the layers.

Conclusion

This chapter has contributed a simple method for hierarchically ranking a set of objects according to multiple characteristics and with multiple objectives in mind. Several extensions and improvements can be made to this method in future efforts. Firstly, in this study only one dataset is used to present the methodology, those produced by the annual Shanghai ranking, to illustrate on the use of our methodology and its implications for research policy. However, even in the case of ranking global universities, other datasets and information sources are available. For instance, the Times Higher Education [60] ranks universities annually, utilizing a different approach. Future research could investigate the combination of information by the use of attributes that come from the different ranking organizations.

Secondly, as stated multiple times, the use of a dominance graph in order to investigate ranking problems is transferrable to different situations. For instance, other researchers could apply this method and test it on other datasets, potentially including a combination of numerical and categorical (ordinal only) data, without the need of an ad hoc weighting scheme, which is very useful under different circumstances. Any research problem in which the objective is to rank or order based on dominance using multiple variables could implement this method as part of the process.

In order to highlight the flexibility of the method presented in this chapter, some extremely different examples are explained. A different use of this method could be for the increased interest in dealing with protected area zoning for conservation as a multi-objective optimization problem [17]. For many years, when multiple geographic areas are examined, the objective is to create a priority ranking of these natural areas based on a variety of variables such as climax condition, educational suitability, species significance, community representation, and human impact [16]. Furthermore, as Smith and Theberge [56] explain, when evaluating natural areas using measurements for a series of criteria, it involves deciding which criteria are important and most significant based on their measurements. The use of a dominance graph would allow alteration and the inclusion or exclusion of certain criteria for each natural area individually and would thus be useful to many different instances across various natural circumstances. For instance, another circumstance for such analysis is the prioritization of farmland preservation for multiple objectives [37] in which the purpose is to preserve it from urbanization.

Another area of obvious application is that of sports [13, 22, 28, 49] and other ranking games in academia, even if they can turn futile when using the wrong assumptions [1]. We are also aware that, after the publication of this paper, a number of other alternative techniques will soon follow that may explore the directed acyclic graph construction hereby presented. We also envision that some researchers may try to exploit the transitive relations of dominance to build up different ranking scores even for objects at the same level. Given that this method is utilized in a global ranking of educational institutions could possibly be transferable to an area so different such as natural area conservation zoning or sports-related ranking activities, it becomes easy to imagine the wide use of dominance graphs in many other ranking activities.

In conclusion, this study adds to the literature a diverse and dynamic heuristic method for ranking multi-variable problems that is transparent and not biased by arbitrary weightings unilaterally and perpetually selected by the ranking organization. We have outlined the utility of this method in the case of ranking global universities using open, publicly available data and, in doing so, provided a novel methodology to approach the ranking of universities globally. This system allows for clearer benchmarking of universities which are at a similar standing. Overall it helps to provide assistance to research policy and decision-makers while at the same time enables a global standing of the universities in the world's landscape of diversified academic offers.

Cross-References

▸ Multi-objective Optimization

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