Managing Resource Allocation in a National Research Foundation with conflicting national objectives

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Abstract

The South African social system suffers from a history of imbalance, and with the advent of democracy, effort is deliberately made to close the social and manpower gap created as a result. The National Research Foundation (NRF) is saddled with the responsibility of funding research programme and developing new generation of researchers amongst its other mandates. In achieving this mandate, they are constrained to operate within the objective of the government in using all the country's instrument of development to redress this historic social imbalance in order to create a more equitable society.

The NRF, therefore, seeks a funding model that can serve as a steering mechanism to achieve the current mandatory policy goals of the organisation to accommodate the systemic needs and also respond to a highly dynamic research and innovation environment while closing the historic manpower gap. These principles and challenges should be addressed within the framework of a new resource allocation model and an associated policy formulated by the NRF to reach its goals to deliver particularly within the constraint of fund availability. In addition to this, there are various types of funding and their possible applications within which the administration of funds must be made without violating funding constraint requirements.

This paper presents an integrated two stage multi-criteria model that is an attempt to meet this challenge of the NRF. An Analytical Hierarchy Process (AHP) model embedded in a Goal Program was developed, in which the conflicting multi-objective goals of the NRF was modelled within the limits of fund availability. The AHP model prioritises the objectives of the NRF and weights the different relevant metrics of the priorities. These weights were used as inputs into the Goal program that seeks to allocate funds based on the relative importance of the objectives as reflected in their metric weights. The last objective created was the fund availability, which is used as the lever to evaluate diverse scenarios based on the possibility of syndicating funds in order to achieve the stated objectives within the funding constraints.

The model was implemented using Microsoft Excel in order to engender the understanding within the executives of the NRF, after which an expanded model that could handle a lot more number of variables and constraints was proposed using R. The solution shows what the NRF needs to do to achieve their diverse strategic goals, and how they may make strategic sacrifices if the constraints become stronger than initially anticipated and resources become sparser. In addition, the model demonstrated that the Foundation was able to achieve the previous years' targets with less resources if it had been implemented earlier, with the savings ploughed into some other areas of need.

Keywords

Keywords: Resource Allocation, Education, Analytic Hierarchy Process, Goal Program

1. Introduction

The National Research Foundation (NRF) is a statutory organ of the state that is stablished by an act of the parliament. It was formed by amalgamating the functions of a number of government funding institutions across the country into a single entity, whose role is to cater for the funding of science research, building of human capacity, providing national science infrastructures and promoting science interest and interaction amongst the general citizenry. The core object of the NRF is to promote and support research through funding, human resource development and provision of the necessary facilities in order to facilitate the creation of knowledge, innovation and development in all fields of science and technology, including indigenous knowledge, and thereby contribute to the improvement of the quality of life of all the people of the Republic.

South Africa is a country with a divisive historical past, and the national government seeks to create social balance within the country, and this has bearing on the environment within which the NRF must deliver on its mandate. While seeking to build capacity, the NRF should seek to redress the historical imbalance while striving to create a core of individuals to drive research excellence within country. These objectives may sometimes be contradictory as there may be the need to continue to capacitate the extant research base while growing others, especially from amongst the previously disadvantaged society.

The current funding model of the NRF is not suitable as a steering mechanism to achieve the current mandatory and policy goals of the organisation – and by association, the system – as it is unable to accommodate the systemic needs and shifts of a highly dynamic research and innovation environment. There is, therefore, a need to develop a new model that is capable of addressing these principles and challenges within the framework of a new resource allocation model and an associated policy formulated by the NRF to reach its goals and to deliver particular outcomes.

There are operational environments of the NRF that would have direct impact on the efficiency of its fund allocation as measured by the achievement of its objectives and as provided by its mandate and the national imperatives as shaped by the global research, opportunities and funding dynamics, and these are discussed next.

Fund allocation is to be done within the contexts of national priorities, fund paucity and fund application constraints. This constraining environment implies that the projects and research funded by the NRF should align with the national priorities. These priorities are dynamic, and therefore, the allocation model should be able to adjust with these dynamics. The dynamics may be influenced by the global trend, national targets, political decisions, and other factors that may affect the government decisions and the goals of the NRF. When there are changes in priorities even within a year, these should be taken into consideration in the next allocation and in the renewal of existing grants. The model should also manage such prioritisation within the constraints of available funds. It is important to state that this fund constraint could be both global and local within the total funds of the NRF. This means, it should consider not allocating more than the total (global) fund the NRF has, and at the same time not allocating more than is desired by the NRF within a particular (local) sector or discipline. It should also enable the NRF to be able to observe the impact of marginal increase or decrease in the local limit set for fund allocation within the entire fund available to the NRF so that the decision about appropriate local limits is also assisted by the allocation system.

While the NRF has many priorities, these priorities are not necessarily complementary. As an example, the NRF has a mandate of helping to create a knowledge society. A measure of this objective might be the number of postgraduates delivered annually. This means it is preferable that funds goes to whatever business unit or grantee that is believed would help to deliver such. But at the same time, it is possible that the business units (or grantees) that produce the highest number of these graduates do not produce enough of a racial group that is also targeted for training. These are conflicting objectives, and as such, there is a need to balance both. The allocation model should, therefore, be capable of guiding to which mix would meet the national targets of the NRF. It may mean selecting the best of each category in achieving the overall best or even selecting those that only balance both objectives while leaving some of those potential beneficiaries that are very good in each of the individual areas out. The goal is therefore to select best mix in terms of these conflicting objectives and not necessarily the best set of achievers amongst the potential beneficiaries of grants.

NRF seeks to allocate its resources in a way to improve the return on its inputs, especially its cash assets. This means while the NRF seeks to find an equitable mechanism of distributing the funds in its coffers, it also seeks to maximise the benefits derivable from such funds. This has two implications: reward and equity. The former implication (the reward part) is that the Business Unit (or grantee) that has demonstrated to have produced superior returns in terms of the achievement of the set objectives of the NRF and in accordance with expectation from the previous funding, should be encouraged by being supported again. This would encourage productive use of resources such that the system has a way of cleaning itself from wasters of the scarce resources of NRF. The second implication (the equity part) means the NRF acknowledges that there are still units and grantees that are believed to have had a history of previous disadvantage and still needs to be supported to progress in careers and whose number actually have to be increased.

The new model should, therefore, be able to determine an equitable allowance to be given to groups, such that even if their productivity is not as high as some others that have been deemed to have not been disadvantaged, such history should work in their favour to allow them social access for enhanced personal development.
The main input towards achieving NRF's objectives is fund, and this has some characteristics that limits NRF's control over the fund's applications, depending on the type of fund received, and based on the objectives of the provision of such fund. The position of fund as an input into NRF is key. While there are other possible inputs that affect the performance of the NRF, fund is a key limitation that influences how many of the intended objectives are achievable, even if the available fund is optimally allocated. Also, NRF has different sources of fund that affect its ability to allocate funds to achieve the best return on their investment. Some funds have no allocation restriction while others do. NRF has to achieve this balance in the allocation of its funds in order not to violate conditions under which funds have been procured and ensure each ring-fenced or contracted fund is spent on purposes for which such funds have been allocated or procured, else, there may be violations of contractual and/or legal restraints. All these constitute the constraints within which the allocation model must work.
This paper provides a proposed solution to the fund allocation of the foundation in such a manner that the allocation is made in a logical way, addressing all the strategic objectives of the NRF, based on the relative importance of each of these strategic goals and the constraint of fund availability and restrictions. The model uses the Analytic Hierarchy Process (AHP) as a logical relative weighting model for the strategic priorities of the foundation. These weights provide inputs into a Goal Programming (GP) model which seeks to optimise the allocation of the funds based on the relative importance of the objectives and fund limitation and restrictions.

1.1 Significance of work

Not many papers are known to have addressed the distribution of research funds while seeking to balance national transformation initiatives within the constraint of funds paucity. This is where this paper seeks to make significant contribution. The NRF has targets in terms of racial balance, gender balance, key knowledge areas, publication of quality papers amongst others, and if there isn't enough funds to do this, all these objectives must be achieved in a delicate balancing manner to achieve the national priorities of transformation, growth and knowledge creation, with all racial and gender groups feeling catered for. These objectives are usually conflicting because while most traditionally favoured races and people groups tend to have acquired competencies that tend to make they more productive. The challenge is to ensure such competencies are put to productive use for the country while previously disadvantaged groups are also capacitated at the same time. Funds availability also has to be considered within this fine balancing act because while it may be possible to syndicate extra funds or ask for virement across priorities, both possibilities are limited and constrained by the law.

The organisation of the paper is now discussed. The first section presents the mandate and the environment within which the NRF operates. The second section discusses the pertinent literature on resource allocation and the techniques adopted in the solution of the allocation problem of the foundation. Section 3 presents the model development procedure followed and the allocation model derived as a result. Section 4 presents the parameterised model, the solution obtained and further scenarios and sensitivity related issues. The final section discusses the results obtained and provides direction for future development of the model for the foundation.

2. Literature Review

The literature review is topically presented, starting with the imperatives of an efficient public administration management in the light of education resource allocation and the models for optimizing allocation of resources.

2.1 The New Public Management and its implications

Most governments strive to optimise the use of resources, especially with the persistent global recession and the attendant cash crunch. The drive to efficiency and optimise resource utilisation in many developed economies have led to the adoption of the new Public Administration (NPM) ideology and its attendant principles and techniques. The NPM strives to provide superior return on public fund deployment through the adoption of many tested and proven principles adopted by the corporate business managers (Tahar and Boutellier, 2013). This paradigm shift has also affected how public higher intuitions and other government parastatals are run and many such institutions have undergone considerable reforms. In the case of higher education, different NPM approaches are used to reform resource allocation. While some approaches establish highly competitive mechanisms relying on formulae, others emphasize strategic choices relying on performance measurement as an organizational learning instrument (Orr et al., 2007 and Tapinos et al., 2005 in Tahar and Boutellier, 2013).

The NPM, especially with its funding and resource allocation strategies has had its own fair share of criticism. There are two main approaches discussed: high touch and high tech approaches. High-touch approaches follow a more qualitative and negotiation-based strategy and put emphasis on strategic choice making. High-tech approaches are quantitative oriented and use a predefined formula to induce competition (Tahar and Boutellier, 2013). The National Research Foundation of South Africa leans more towards the high touch than the high tech, striving rather to achieve strategic national priorities over simply driving for improved productivity. While considerations for the latter is also imperative, more emphasis is given to the former. This influences the selection of the most useful operations research technique adopted for NRF-SA's resource allocation programme, and this would be discussed later.

Funding is a key government instrument, and the budgetary and allocation mechanism of the government is usually utilised to drive diverse strategic initiatives. There are two main types of funding sources for Universities. The first is core funding, which comes from the government budgetary allocations and is based on detailed line item budgets; the second is contract funding, which is based on agreement with some partners or funding agencies. The generally perceived problem of core funding is guaranteeing the creation of value from such, while that of contract funding is the possible lack of flexibility (ibid). Balancing between this two is challenge to universities and funding agents, and this is not an exception at the NRF. Planning and management of fund can be indicator based or global budgeting based. Global budgeting focuses on the definition of global qualitative and quantitative goals for research and teaching and provide a global budget. This approach helps such institutions to gain operative autonomy and act strategically to reach their goals. The degree to which the goals have been achieved will be evaluated, and results will be used to support resource allocation decisions (Braun, 2001 in Tahar and Boutellier, 2013). This approach serves to prevent the fund provider in becoming directly involved in the administration of the fund, which might usually become counterproductive.

2.2 Resource Allocation challenges in Public and educational Practices

Determining how to allocate resources is always a challenging decision, and many organisations have had to lean on some models or techniques to assist in allocating the funds as well as in measuring the efficiency of such allocations, especially in driving their strategic goals. A brief review of such is provided next. The health sector seems to be the main area that has documented records of trying to do this, even though most report seems to be more focused on evaluating performance of allocation rather than in guiding the allocation itself. This would not be the best way to do so, because such approach only serves evaluation purpose as opposed to giving prescriptive solutions. Reports of resource allocation would be reviewed first in general, and then the emphasis would progress to some known prescriptive solutions.

In the health sector, some resource allocation challenges and efforts have been reported. Jing, Wen-Yang and Wei (2016) considered appropriate heath resource allocation to be the primary condition for protecting all society members to obtain effective and equity health service. Equity is an important principle in health administration because people should be able to access good health facility irrespective of their status or earning capacity. They studied the level of equity in the allocation of health resources in different areas of Yunnan province of China using Theil index analysis. It is capable of measuring both absolute and relative inequality amongst beneficiary units. The Theil index is, however, not an allocation mechanism per se, but an index to estimate the level of disparity (or equity) in the allocation of diverse hospital resources between and within different areas. Joseph, Rice and Chuyu (2016) reported a similar study in Georgia, USA, where they used multiple regression technique. Gorsky and Millward also did an equity study in the UK using a more qualitative approach, the Advocacy Coalition Analysis.

Shishi et al (2018) studied what features of health care professional training evaluation studies are important for decision-making by policy-makers in low and medium income countries with China as the particular case. They used the Kirkpatrick model, which accepts qualitative data as inputs. They concluded that an evaluation whose main focus is narrow and based on direct training outcomes does not provide sufficient information for policy-makers to make good future decision. Their model also does not provide an optimal allocation mechanism or model for health resources training.

Yaylali et al (2016) presents an allocation model for the optimisation of the distribution of funds for the management of HIV treatment and prevention in four centres for the control of diseases in the health departments in three states of America. The model allocated a fixed budget among HIV interventions and risk subpopulations in order to maximise the number of new infections prevented. They used a combination of linear programming model and the Bernoulli process model in the allocation framework using various durations of intervention. The Bernoulli process model used behavioural data and intervention efficacy to determine annual transmission and acquisition risk, with and without each intervention. The optimization model used the budget amount, intervention costs, and each health department's epidemic profile, including the maximum reach of each intervention. It was implemented in Microsoft excel with solver add-in and visual basic interface. Three of the 4 pilot sites found the model and its results useful and sought to implement them in their budget allocation decisions.

In some other sectors, Khoshnevis and Teirlinck (2017) studied resource allocation in Research and Development (R&D) driven firms in Belgium. They used input based Data Envelopment Analysis (DEA) with constant and variable return to scale to evaluate the performance of the firms. They reported different level of (in)efficiency levels technical and scale terms. They also observed that firm size and industry sector has direct influence on the efficiency of the firms studied. This study is also purely evaluator and not prescriptive in that it does not actually propose how the resources should be allocated, but only reported on efficiency levels attained given the level of resources deployed.

Kosterev and Litvinov (2016) discussed the modernisation of the infrastructures of power utilities in the face of funds constraint amongst many competing goals and possible infrastructures. They state that such decision is complicated because it involves both economic and technical complexities, are multi-objective, involve significant level of uncertainties while there is hardly sufficient funds for the execution of all necessary infrastructure projects. Also, while simple assumption of determinism tends to be made in many such cases, the level of specificity of variables is actually far from such precision. They used fuzzy statistical method in modelling the system when developing the Pareto efficiency frontier. The focus of this model is more on the minimisation of the risk of an emergency situation under conditions of a large number of uncertainties. They followed a three-step procedure of first forming the set of feasible solutions, determining how nest to reduce the risk of an accident given the candidate solutions and then forming the Pareto effective subset from amongst the candidate solutions at which to reach compromise allocation of funds at which the minimum possible risk of accident is estimated. From this, they developed policies for the replacement of assets to minimise the risk inherent in the system that could lead to accidents based on the technical characteristics of the electric system.

Some other resource allocation challenges have also been reported in the education sector. Equity and productivity are themes that ring through many resource allocation programmes of a number of higher institutions in many countries, irrespective of the development level of such countries. Some of these are reported next.

Zhu, Zhang and Wang (2018) discussed the challenges of efficient quota allocation of PhD space in a Chinese University. With the ambitious plan of transforming the Chinese economy into a knowledge and innovation driven economy, there was the desire to create “world-class” universities. Such universities need a plethora of research and innovation skills and there is the need to balance this given the limited resources available to support research and development in the universities. This has led to tight competition among and within the Chinese universities during the process of allocation of resources, and this has often led to disputes. They then proposed a comprehensive index method, which uses a weighted combination of the scores of the different schools involved on some selected indices to create an aggregate score to determine the level of PhD slot allocation to each school. This allocation was then tested for efficiency using the Data Envelopment Analysis (DEA) technique.

Okhremtchouk (2017) presented the challenges of making supplementary allocations towards the needs of previously marginalised students in the United States. Supplemental programs (encompassing categorical grants) are restricted funds intended to meet the needs of various, often marginalized, student populations. The goal of this initiative is to improve the competitiveness of a particular category of students by bringing the students whose home language of studies is not English language to a reasonable level of comprehension such that they can compete favourable in class when learning with the traditional English learners. There have been call for evaluation of the program because the results seem not to fully justify the expenditure made on such programmes. One of the main one explanations proffered for this disconnect might stem from preexisting dynamics (political and otherwise) linked to various hierarchical systems within local organizational structures that oversee and, therefore, directly influence the allocation of supplemental resources meant to support programs designed to address students’ specific academic needs. It was found that when funding formulas are not exclusively tied to policy objectives, allocated funds often fail to target the intended student subgroups. In some cases, these ambiguous formulas even allow resources to be channeled to districts without evident use for these funds, often leading to (expected) misappropriation of these dollars (Timar, 2007 in Okhremtchouk, 2017)

Another resource allocation paradigm has also been reported by Abdullai and Hickey (2016). They noted that initial hopes of development as a result of democratic entrenchment in Africa have been undermined because of political clientelism, which often seem aimed at maximizing voter support rather than proceeding from either universalist principles or even any form of citizens’ needs. African politicians target disproportionate public resources towards areas with the most loyal political supporters, both as a reward for existing and previous political backing and as a down payment for its continuation. This model of allocation seems to defy every logic of productivity or equity because the political players only seek to consider how the resource allocation would benefit their personal future ambitions. It also defies equity principle because regions needing necessary interventions are not really considered. The research studies distribution of national projects in Ghana, and seeks to generalise for Africa.

Hammarfelt (2016) studied the filter down effect of performance based resource allocation in Sweden Universities. They classified the use of bibliography as a basis for fund allocation into three levels: the macro level (national), the meso level (institutional) and the micro level (individual).They used bibliographic studies to seek an understanding of how performance based allocation influences the productivities of the university and its staff members at a lower level. They adopted questionnaire based approach and did a mapping of the Swedish academic landscape based on bibliometric indicators and systems. This study does not consider how to allocate funds amongst universities, but focuses on how the universities react based on the applicable bibliometric performance measurement techniques.

2.3 Operations Research in education

Operations Research (OR) has been applied in diverse context of educational planning. Johnes (2015) is a good compendium of such diverse applications in education. An area that has been particularly noted to have benefited from the application of OR techniques in education is resource allocation, and many such applications include top-level planning and distribution of resources. While OR started as a joint effort between the military and civilian scientists during the Second World War, it promptly found applications in civilian contexts immediately after the war. It was however noted that its penetration to public arena was slower, probably because of the lower drive for profitability and efficiency in the public services domain. Over time, areas such as education, health, police and fire services are amongst those that seem to have benefited much.

The two broad areas of application are firstly planning and resource allocation and secondly performance measurement. Incidentally, these two areas are important in resource allocation problems of higher institutions and funding institutions like the NRF. This becomes particularly important because in most countries, funding of education is usually done by the government because the people are the greatest capitals the country can develop. Governments, therefore, need to know not only how many students to expect and support at different level of education, but also how much would be necessary and/or sufficient to support them (ibid).

Goal Programming with AHP weights

While most initial models of OR have been single objective, a number of techniques to handle multi-objective problems have been developed. Analytic Hierarchy process (AHP) and Goal Programming (GP) are two such techniques. AHP was first proposed by Saaty (1980). It provides relative weights of importance amongst competing objectives through a series of pair-wise comparison among the objectives. One of the strengths of the AHP is the ability to check the consistence of the ranking of objectives through is Consistency Index (CI), which utilises the principles of Eigen value from the pairwise comparison matrix.

While the AHP has many good features, one of its limitations is not being able to make trade-off to ration resource among many alternatives. It can guide in deciding the most logically preferred option, but when there is the desire to accept multiple alternatives, but to different levels of allocation of rations, it may not be a good choice of technique. This is one of the main strengths of Goal Programming (GP), which was first utilised by Charnes, Cooper and Ferguson (1955). The main characteristics of the GP are: firstly, all constraints in a Linear Program (LP), together with the objective function, are considered as objectives, but with different level of priorities; secondly, rather than treat the right hand side values of an LP as a hard constraint, they are considered to be target values that could be violated, but depending on the level of importance of the objective. This makes it possible to determine the level of violation necessary to under or overachieve a particular goal, if it makes a better contribution towards the greater goal of the model.

Combining AHP and GP is a good technique where the strength of a technique is needed to complement the weakness of the other. For instance, it is possible to use the AHP to determine the relative weights of the multiple objectives of the constraints of the goal program, which are actually treated as priority alternatives in the AHP. The GP is then used to determine the relative trade off levels to be achieved in each of the priority objectives towards the achievement of the global objective. The relative rate of trade-off in the GP is dependent on the objective weights estimated for each GP objective from the weight matrix derived from the AHP technique. Some such applications are reported next.

Can et al (2017) used AHP, GP and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) to select the appropriate maintenance strategy for hydro-electric power pants. AHP was used for weighting of the nine most important priorities selected using TOPSIS, while GP was used for the determination of the appropriate maintenance priorities and levels. Cayir et al used the same combination of TOPSIS, AHP and GP in planning the level of investment to be made in renewable power plants, using binary GP. Chen et al (2016) used AHP to determine the level of penalty of soft constraints in a GP model of staff scheduling problem in an integrated medical staff allocation and staff scheduling in uncertain environments. Other such AHP/GP combination can be cited.

3. Model and solution procedure development

This section presents the development of the integrated AHP and GP models used to address the resource allocation. It is imperative to first discuss further the context of NRF's operations.

3.1 Notations

The following notations are adopted throughout the model development. Let

x, y be any integer numbers

S, indexed with $s = 1,2, \dots, m$, be the set of some objectives.

I_i, indexed with $(s, i), s = 1,2, \dots, m, \ i = 1,2, \dots, n$, be the set of performance indicators for a strategic objective S_s.

A be a square matrix, indexed with $a = 1,2, \dots, b$ containing the pairwise comparison of the relative importance of some objectives or goals to one another

A_{norm} be a square matrix, indexed with $a = 1,2, \dots, b$ containing the normalised pairwise comparison of the relative importance of some objectives or goals to one another

$\boldsymbol{w}$, indexed with $a = 1,2, \dots, b$ be the set of weights defined on a set of objectives or goals, e.g. the strategic objectives, such that w_s is the ideal relative importance of the strategic objective S_s

$\boldsymbol{w}^{'}$, indexed with $a = 1,2, \dots, b$ be the set of weights defined on a set of objectives or goals, e.g. the strategic objectives, such that w_s^i is the maximum relative importance of the strategic objective S_s achievable given pairwise comparison matrix, A, of the decision maker

Δ be a number needed in the determination of the weights w_a indicating the relative importance of an objective or a goal, e.g. the strategic objective S_s

Δ_{max} be a number needed in the determination of the weights w_a^i indicating the relative importance of an objective or a goal, e.g. the strategic objective S_s

$\boldsymbol{z}$ be a set of some decision variables in an optimisation model, e.g. the performance metric of $I_{s,i}$ for a strategic objective S_i

T be a set of target values for some goals, indexed by $a = 1,2, \dots, b$

$\boldsymbol{d}$ indexed by a variable $a = 1,2, \dots, b$ be the set of the deviation variables that determines the level of under- or over-achievement of the target in the set T value for the set goal, such that,

$$d_a = d_a^- + d_a^+ \qquad (1)$$

d_a^- is the under achievement of the target value of a goal,

d_a^+ is the over achievement of the target value of a goal,

$c_{i,a}$ be the cost of achieving a unit measure of a performance indicator I_i given a target goal, T_a

3.2 Solution Procedure for AHP

We define

$$A \triangleq \begin{bmatrix} \frac{w_1}{w_1} & \cdots & \frac{w_1}{w_b} \\ \vdots & \ddots & \vdots \\ \frac{w_b}{w_1} & \cdots & \frac{w_b}{w_b} \end{bmatrix}$$

This means A is a square matrix such that for each cell A(x,y), if $\frac{w_x}{w_y} = 3, x = 1,2, \dots, b \ \ y = 1,2, \dots, b$, then, goal x is 3 time more important than goal y.

We need to recover the vector $\boldsymbol{w} = [w_{1,\dots,} w_b]$, such that

$$A\boldsymbol{w}^T = \Delta \boldsymbol{w}^T \qquad (2)$$

A trivial solution to equation 2 is $\boldsymbol{w} = [\boldsymbol{0}]$, and the non-trivial solution is $\Delta = b$. This non-trivial solution is attainable if the decision maker is perfectly consistent, which usually is not the case in most instances. A good solution is, therefore, the one that is as close to b as possible, and this Δ value would be called Δ_{max}. The goal is to set a limit below which Δ_{max} must not fall, and with the Δ_{max} value, we obtain the corresponding $\boldsymbol{w}^{'}$ vector.

Saaty (1980) provided an algorithm to estimate $\boldsymbol{w}'$ as follows:

a. Normalise the entry in each column using the column's $\frac{w_x}{w_y}$ total.

$$\text{i.e.} \quad A(x,y)_{norm} = \frac{\frac{w_x}{w_y}}{\sum_{x=1}^{b} \frac{w_x}{w_y}} \tag{3}$$

b. Find $\boldsymbol{w}'$ by averaging for each row

$$\text{i.e.} \quad w_y' = \frac{1}{b} \sum_{y=1}^{b} A(x,y)_{norm} \tag{4}$$

c. Check the $\boldsymbol{w}'$ values for consistency by the following:

   i. Calculate $A\boldsymbol{w}'^T$

   ii. Compute

$$\frac{1}{b} \sum_{a=1}^{b} \frac{a^{th}\ entry\ in\ A\boldsymbol{w}'^T}{a^{th}\ entry\ in\ \boldsymbol{w}'^T} \tag{5}$$

   iii. Subtract b from your answer from equation 5.

   iv. Divide the result of step $C(iii)$ by $b - 1$

   v. Compare the answer of step $C(iv)$ to the value obtained for a randomly generated relative weight equivalent for a particular b value called the Random Index (RI)

      i. If step $c(v)$ is less than the random value by an acceptable ratio, usually taken as 0.1 for most applied cases, accept the weight vector $\boldsymbol{w}'$

      ii. Else, reject the pairwise comparison matrix for inconsistency and so, reject the weight vector, $\boldsymbol{w}'$, as well

3.3 GP Solution procedure

The Goal Program (GP) could be a pre-emptive GP or a weighted GP model. A weighted model was chosen because it adjusts the trade off in the achievement of targets for each goal based on the relative weight (or importance) of each of the goals, without necessarily achieving a more important goal fully before achieving a less important goal in any way. This makes it possible to have trade-offs without necessarily sacrificing any objectively completely, but only to an extent to which the goal is specified as being more (or less) important than others as may be necessary.

The weight vector derived from the AHP model becomes an input into the GP to be used for resource allocation. The deviation variables of the GP are weighted by the weight vector, $\boldsymbol{w}'$, generated from AHP. The GP model is

Minimise

$$\sum_{a-1}^{b} w_a' \, d_a \tag{6}$$

s.t

$$\sum_{a=1}^{b} c_{i,a} \, I_a + w_a' d_a = T_a \tag{7}$$

The objective of the GP model is to minimise the weighted sum of the deviational variables. This is shown in Equation 6. In applying the weight w'_a to the goals, the deviational variable (d_a^-, d_a^+) to which the weight is attached depends on the direction of optimisation of the target value. For instance, if the goal is to maximise a goal's target, d_a^- has the weight w'_a while d_a^+ has a zero weight and vice versa. If the target is to be exact, then both d_a^- and d_a^+ have the weight w'_a.
Equation 7 is the set of constraints for the target values of the goals that need to be achieved by the resource allocation process. These values were normalised by dividing each $c_{i,a}$ value by the target value for the goal T_a. This is to prevent some constraints that have high input ratios to other constraints from dominating the sensitivity of the model to the w'_a values. Hence, equation 7 was actually implemented as equation 8.
The conflicting objectives to be addressed in the resource allocation process is finally handled here. Each of the objectives are captured as constraint targets with their deviational variable. For instance, the need to fund a minimum number of people within particular racial groups is indicated as target. The need to maintain a minimum ratio balance in case of insufficient funding is also captured in the constraint equation. The need to minimise deviation from funding targets and must reflect in the constraint targets. There is also ensure that a traditionally trained sector is accommodated in such a manner that while everyone is made to understand the importance of racial inclusivity, the imperative of national productivity and preservation of people of knowledge is also achieved. All these objectives are conflicting given that all groups are funded from the same pot.

$$\sum_{a=1}^{b} \frac{c_{i,a}}{T_a} I_a + w'_a d_a \ = 1 \tag{8}$$

With the AHP and GP models formulated as stated, the implementation and solution process for the sample parameters were done, and this is discussed next.

4. Model Parameterisation and Solution

The model was implemented in Microsoft Excel with a solver add-in. The parameterisation procedure is presented first, and then, the model solution. The first exercise is to provide relative ranking of the national strategic objectives with respect to each other. The NRF has a number of Strategic Business Units that are responsible for achieving one or more of these strategic objectives. For the purpose of this work the focus is on the unit that provides grant for supporting students and researchers (HICD – Human and Infrastructure Capacity Development), which is related only to priority 1 and part of priority 2. This unit consumes almost 60 percent of funds of the NRF. The bigger model treating all the priorities is not discussed. While there is definitely an interaction between all the metrics of the strategic objectives across all the priority areas, only the student and research granting objectives are illustrated here.
The allocation of funds should seek to address previous imbalances in the human capacity structure of the country by providing preferential allocation along two main lines: race and gender. In addition, due to the need to develop research capacity in the country, there is the need to invest more in studies that can lead directly to capacitation for research purposes, and hence, a third consideration is level of study. The AHP technique was, therefore, applied in a robust environment of debate amongst the decision makers to come up with an agreeable relative weight amongst these three variables: race, gender and level. This leads to a weight vector of $\boldsymbol{w}' = [0.63, 0.26, 0.11]$ was derived with a CI factor of 0.036. With RI being 0.58 for 3 competing goals, CI/RI ratio of 0.062 was determined, and this is deemed acceptable, being less than the 0.1 limit.
Next is the pairwise comparison of the lower level metrics for race, gender and level. The weight vectors CI, RI and CI/RI values for each of these three higher level metrics were:
Race has four lower levels: African, Coloured, Indians and Whites. The

$$\boldsymbol{w}' = [0.52, 0.2, 0.2, 0.08],\ CI = 0.019,\ RI = 0.9,\ \frac{CI}{RI} = 0.022$$

Gender has two lower levels: made and female.

$$\boldsymbol{w}' = [0.6, 0.4],\ CI = 0\ \ R = 0$$

Level has five lower level metrics: Honours, masters, doctorate, post doctorate and researchers.

$$\boldsymbol{w}' = [0.13, 0.26, 0.5, 0.35, 0.07],\ CI = 0.091,\ RI = 1.12,\ \frac{CI}{RI} = 0.081$$

All weights are seen to be acceptable consistent, and form the coefficients of the deviational variables.

Next is the discussion of the priority goals and targets. Based on the national plans, current realities and other factors, priority areas and their target values were determined. Forty human capital categories and their target values were then set as shown in Table 2. The weights for each of these categories were composed from the weights of the key priority areas to which each of these belong. Some aggregate numbers levels and ratio of numbers allocated amongst levels were also defined (e,g, minimum total of males, minimum total of females, minimum ratio of doctorate to honours, etc). This leads to a total of 46 categorical targets involving student and research groups.
The last constraint introduced was funding constraint. The average unit cost of supporting the different level of students and researchers (honours through postdoc to researchers) was calculated, and a minimum fund level of half a billion South African Rands (ZAR) was set as target. The weight of the funds deviation variable was set as a variable ranging from 0.1 to 5 and several scenarios were evaluated. This makes the fund constraint to act as a weight on a lever balancing against other priority areas such that we can observe the impact of limitation of funds on the achievement of the national strategic objectives set for the NRF in terms of capacity development. When the deviational weight on fund was low, this allows the violation of the target value of funds set and selects the best combination to meet all goals at the minimum possible value, although at a cost much more than the half a billion ZAR. As the weight is increased gradually to 5 for the deviational weight of the fund constraint, it starts to gradually prevent the violation of the funding limit of half a billion ZAR set, but begins to strategically decrease the number of students and researchers funded in the different categories.
The average funding cost for the 5 levels in thousand ZAR were 35, 40, 110, 305 and 75 for honours, masters, doctorate, postdoc and researchers respectively.
With weight set at 0.1, all targets were met and some exceeded a little bit at a cost of R1.66 billion. With the weight progressively increased to 5 for the deviational variable of fund, different numbers of each of the student and researcher categories, with the least prioritised areas being progressively decreased first.
Also, a full funding model for students was evaluated. The goal of the full funding model is to increase student grants so that students can fully concentrate on studies and research and graduate more quickly. The relevant cost for full funding was estimated and used as the cost vector. The maximum number of students that can be produced in each category of race, gender and level were determined as well. This is followed by sensitivity analysis to test the robustness of the model.

5. Discussion of findings

This means with about R1.66 billion, the capacity plan of NRF could be fully achieved with an appropriate selection of students from all categories. This has two implications. The target could be achieved at a cost lower than what has been spent previously. Secondly, if the government seeks to increase the number of students and researchers supported, there is a logical way of estimating the minimum amount needed while still attaining the target racial and gender balance together with the focus on the development of researchers. Also, with the government of South Africa considering a full funding model, it became obvious how many students would need to seek alternative funding for their studies so that the government could budget appropriately for the Student Financial Aid Programme.
In addition, since funding for National Research Foundation comes in the form of core funding and project (or ring fenced) funds, it becomes easier to put all funds to better use such that all necessary targets of the diverse types of funds can be allocated appropriately through the appropriate targeting of the different categories, although that has not been done at the current level for the NRF in South Africa.

6. Conclusion

Education is an important part of any economy today as all countries seek to move towards knowledge driven economy. It, therefore becomes inoperative for governments to seek scientific methods allocate their study and research funds in order to get the best deal for the country. It is also important to determine minimum and maximum limits of what is achievable so that different government departments and units do not make unrealistic demands from each other. This model would be expanded in the future to include all other propriety targets of the NRF, and a non-deterministic model would be considered later.

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Table 1: National priorities and their indicator metrics with their importance ranking

Rank	Priorities and Metrics
1	**Priority 1: Transformation of Human Capital base**
	Metric 1: Number of black female researchers produced
	Metric 2: Number of white female researchers produced
	Metric 3: Number of black male researchers produced
	Metric 4: Number of white male researchers produced
1	**Priority 2: General Human Capital Development**
	Metric 1: Number of publications (Web of Science)
	Metric 2: Number of rated researchers
	Metric 3: Number of PhDs supported
	Metric 4: Number of Masters supported
	Metric 5: Number of postdoc and emerging researchers supported
1	**Priority 3: Knowledge generation**
	Metric 1: Quality of publications (Impact Factor)
	Metric 2: Publications with Africa authors
	Metric 3: Publications with Rest of the World authors
4	**Priority 4: Grow NRF influence**
	Metric 1: Number of public reached with science and engineering awareness
	Metric 2: Number of learners reached
	Metric 3: number of users of National Facilities (NFs)
	Metric 4: Number of researchers in Science and Engineering activities
3	**Priority 5: Internationalisation**
	Metric 1: Number of grants for international partnered research made (Africa and Rest of the World)
	Metric 2: Number of bi- and multilateral agreements
	Metric 3: Number of co-publications
	Metric 4: Access to international platforms
2	**Priority 6: Infrastructure provision**
	Metric 1: Support for NF - large infrastructure
	Metric 2: Support for NF - small infrastructure
	Metric 3: Support for Maintenance
	Metric 4: Support for equipment
	Metric 5: Support for salaries at NFs
5	**Priority 7: Priority Knowledge Areas**
	Metric 1: Support for Knowledge Area 1
	Metric 2: Support for Knowledge Area 2
	Metric 3: Support for Knowledge Area 3
	Metric 4: Support for Knowledge Area 4

Table 2: Human Capital categories, weights and annual targets

Race =0.63		**Gender = 0.26**		**Level = 0.11**		**Category**	**Weight**	**Target**	**Variable code**
African	0.52	Female	0.6	Honours	0.13	African Female Honours	0.5	746	z1
Coloured	0.2	Female	0.6	Honours	0.13	Coloured Female Honours	0.3	207	z2
Indian	0.2	Female	0.6	Honours	0.13	Indian Female Honours	0.3	265	z3
White	0.08	Female	0.6	Honours	0.13	White Female Honours	0.22	878	z4
African	0.52	Male	0.4	Honours	0.13	African Male Honours	0.45	717	z5
Coloured	0.2	Male	0.4	Honours	0.13	Coloured Male Honours	0.25	124	z6
Indian	0.2	Male	0.4	Honours	0.13	Indian Male Honours	0.25	265	z7
White	0.08	Male	0.4	Honours	0.13	White Male Honours	0.17	655	z8
African	0.52	Female	0.6	Masters	0.26	African Female Masters	0.51	865	z9
Coloured	0.2	Female	0.6	Masters	0.26	Coloured Female Masters	0.31	240	z10
Indian	0.2	Female	0.6	Masters	0.26	Indian Female Masters	0.31	308	z11
White	0.08	Female	0.6	Masters	0.26	White Female Masters	0.23	1019	z12
African	0.52	Male	0.4	Masters	0.26	African Male Masters	0.46	832	z13
Coloured	0.2	Male	0.4	Masters	0.26	Coloured Male Masters	0.26	144	z14
Indian	0.2	Male	0.4	Masters	0.26	Indian Male Masters	0.26	308	z15
White	0.08	Male	0.4	Masters	0.26	White Male Masters	0.18	760	z16
African	0.52	Female	0.6	Doctorate	0.5	African Female Doctorate	0.54	579	z17
Coloured	0.2	Female	0.6	Doctorate	0.5	Coloured Female Doctorate	0.34	161	z18
Indian	0.2	Female	0.6	Doctorate	0.5	Indian Female Doctorate	0.34	206	z19
White	0.08	Female	0.6	Doctorate	0.5	White Female Doctorate	0.26	682	z20
African	0.52	Male	0.4	Doctorate	0.5	African Male Doctorate	0.49	557	z21
Coloured	0.2	Male	0.4	Doctorate	0.5	Coloured Male Doctorate	0.28	97	z22
Indian	0.2	Male	0.4	Doctorate	0.5	Indian Male Doctorate	0.28	206	z23
White	0.08	Male	0.4	Doctorate	0.5	White Male Doctorate	0.21	509	z24
African	0.52	Female	0.6	PostDoc	0.18	African Female PostDoc	0.5	147	z25
Coloured	0.2	Female	0.6	PostDoc	0.18	Coloured Female PostDoc	0.3	30	z26
Indian	0.2	Female	0.6	PostDoc	0.18	Indian Female PostDoc	0.3	55	z27
White	0.08	Female	0.6	PostDoc	0.18	White Female PostDoc	0.23	183	z28
African	0.52	Male	0.4	PostDoc	0.18	African Male PostDoc	0.45	150	z29
Coloured	0.2	Male	0.4	PostDoc	0.18	Coloured Male PostDoc	0.25	26	z30
Indian	0.2	Male	0.4	PostDoc	0.18	Indian Male PostDoc	0.25	55	z31
White	0.08	Male	0.4	PostDoc	0.18	White Male PostDoc	0.17	137	z32
African	0.52	Female	0.6	Researcher	0.07	African Female Researcher	0.49	206	z33
Coloured	0.2	Female	0.6	Researcher	0.07	Coloured Female Researcher	0.29	95	z34
Indian	0.2	Female	0.6	Researcher	0.07	Indian Female Researcher	0.29	113	z35
White	0.08	Female	0.6	Researcher	0.07	White Female Researcher	0.21	825	z36
African	0.52	Male	0.4	Researcher	0.07	African Male Researcher	0.44	512	z37
Coloured	0.2	Male	0.4	Researcher	0.07	Coloured Male Researcher	0.24	124	z38
Indian	0.2	Male	0.4	Researcher	0.07	Indian Male Researcher	0.24	154	z39
White	0.08	Male	0.4	Researcher	0.07	White Male Researcher	0.16	1259	z40

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