International Conference on Hydroinformatics

2014

Evaluation Of Decision Making Methods For Integrated Water Resource Management Under Uncertainty

Thomas Peter Roach

Zoran Kapelan

Michelle Ledbetter

Ben Gouldby

Steven Wade

See next page for additional authors

Authors

Thomas Peter Roach, Zoran Kapelan, Michelle Ledbetter, Ben Gouldby, Steven Wade, and Ralph Ledbetter

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

EVALUATION OF DECISION MAKING METHODS FOR INTEGRATED WATER RESOURCE MANAGEMENT UNDER UNCERTAINTY

TOM ROACH (1,2), ZORAN KAPELAN (1), MICHELLE LEDBETTER (2), STEVEN WADE (2), BEN GOULDBY (2), RALPH LEDBETTER (2)

(1): University of Exeter, Centre for Water Systems, Harrison Building, North Park Road, Exeter EX4 4QF, UK

(2): HR Wallingford, Howbery Business Park, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BA, UK

ABSTRACT

This paper evaluates two established decision making methods and analyses their performance and suitability within an Integrated Water Resources Management (IWRM) problem. The methods under assessment are Info-Gap decision theory (IG) and Robust Optimisation (RO). These methods have been designed to aid decision making under severe uncertainty but differences exist in their approach and attitude to robustness and risk. For example, the Info-Gap methodology offers solutions that provide a localised robustness of sufficing over a wide range of uncertainty, but is highly dependent on the selection of the starting point. Robust Optimisation concentrates on optimising for a global robustness and cost, independent of likelihood assumptions. These methods were applied to a case study resembling the Sussex North region in England, assessing their applicability at improving the IWRM problem and highlighting the strengths and weaknesses of each method at selecting suitable adaptation strategies under climate change and future population uncertainties. Both methods show potential in water resource adaptation planning, but present conflicts in their global vs local definitions of robustness. Pareto sets of robustness to cost were produced for both methods and highlight RO as producing the lower costing strategies for the vast majority of varying target robustness levels. However, IG generally produces strategies that provide greater maximum and average risk reduction across the range of potential scenarios, indicating a trade-off of higher costing solutions for greater risk aversion.

INTRODUCTION

Water companies and utilities in the UK are required to produce Water Resource Management Plans (WRMPs) every five years that outline their future strategies for maintaining a secure water supply to meet anticipated demand levels. Regulatory frameworks differ around the world but in many countries similar plans are developed under the auspices of Integrated Water Resources Management (IWRM) programmes. The plans justify new demand management and water supply infrastructure needed and validate management decisions. One of the greatest problems now facing decision makers in the water industry are the increasing uncertainties in the variables used in estimating the balance of supply and demand due to increasing levels of climate change and population growth. WRMPs in the future will need to deliver plans that can adapt water supply systems to face a widening variation of possible future states; with increased consideration to uncertain water availability, resource deterioration and demand levels, all of which are currently under-assessed within these management decisions [1]. The two decision making methods under investigation have been designed to aid in decision making where potentially severe uncertainties may exist.

The current UK approach laid out in the Environment Agency's Water Resources Planning Guideline [2] is to produce a "best estimate" of future deployable output using UKCP09 projections and to develop a strategy to deliver an acceptable balance given mean changes in the supply and demand. This produces a single best estimate of the likely effects of climate change and encourages a "predict and provide" type approach to water resources. This procedure does not encourage the most robust or flexible options to be derived, merely one estimated to be adequate to fulfil average expectations. Marginal Target Headroom is then added to cover estimate errors and uncertainties. Target Headroom is the allotted "extra room" or "error safety margin", given to cover the range of uncertainties between best estimates of supply and demand [3] which are incorporated to reduce the probability of shortage occurring. However, this does not safe-guard against the more extreme projected scenarios, such as severe changes in individual supply source availability at peak demand periods [2][4].

This paper evaluates the application and performance of Info-Gap and Robust Optimisation to an IWRM problem under climate change and demand uncertainty. First the general IWRM problem is described followed by the concepts of risk, robustness, strategies and costs before giving a brief description of the two decision making methods under review. The case study is then outlined followed by results and discussion exploring the performance of each method and evaluating the concepts of robustness and risk reduction.

METHODOLOGY

IWRM Problem Definition

The IWRM problem is defined here as the long-term water resources planning problem of supply meeting future demand. The aim is to, for a given long-term planning horizon, determine the best adaptation strategy (i.e. set of interventions scheduled across the horizon) that are required to upgrade the existing regional WRM system that will maximise the robustness of future water supply whilst minimising the total cost of interventions required. Robustness of water supply (see definition below) is evaluated across a number of different, pre-defined supply and demand scenarios which are used to represent uncertain future climate change and population. The above problem is solved by using the two different decision making methods, each with its specific implementation. The results obtained by using the different decision making methods are compared after all solutions are re-evaluated using the definitions of risk, robustness and costs outlined below.

IWRM Simulation Model

A water resource network model has been developed that simulates, using a daily time step, the supply and demand balance of a regional water supply system over a pre-established time horizon. Different future scenarios and adaptation strategies can be input to the system, analysing the performance of each system combination via risk of water deficit results.

Risk of a Water Deficit

The failure is defined here as water supply not meeting the demand required. Eq.(1), calculates a risk of a water deficit occurring (R_d) in the likelihood x severity form:

$$R_d = \left(\frac{\sum_{j=1}^{N} d_t}{T}\right) \times \sum_{j=1}^{N_t} \Delta V_j \qquad (1)$$

Where: d = a day registered with a water deficit; T = the total number of days in the planning horizon (or segmented time horizon); ΔV = the volume of a water deficit recorded in a day; j = the index of timesteps and N_t = total number of timesteps in the planning horizon.

Robustness of Water Supply

Robustness of long-term water supply is defined here as the fraction (i.e. percentage) of future scenarios of supply and demand that result in an acceptable system performance. For example, if 90 out of 100 scenarios are deemed to have been met then the robustness of the water supply is 90%. The acceptable performance is defined as risk of water deficit (see Eq.1) being below the target, i.e. the pre-specified level for the full duration of some long-term planning horizon.

Adaptation Strategies

Different adaptation strategies (q) can be produced by employing different combinations of new potential water resource options (w) arranged over a strategic planning horizon. The total costs of strategies in the form of Net Present Values (NPVs) are derived using Eq. (2). This applies an annual discount rate of 3% (d) to both the estimated capital (C) (£M) and operation costs (O) (£M/yr); where: i = the resource option index; N_o = the number of resource options and dt = the timestep duration (years).

$$NPV_q = \sum_{i=1}^{N_o}\sum_{j=1}^{N_t}\left[\frac{w_{ij}C_i}{(1+d)^{(j-1)dt}} + \frac{w_{ij}O_j dt}{(1+d)^{(j-1)dt}}\right] \qquad (2)$$

Decision Making Methods

Method 1. Info-Gap Decision Theory (IG)

Info-Gap decision theory (IG) emerged in response to design and planning decisions under severe uncertainty. It provides a quantified theory of robustness over a localised area of uncertainty and favours robustness of satisficing or ‘sufficing’ in its approach to decision making [5]. A strategy of satisficing robustness can be described as one that will satisfy the minimum requirements (perform adequately rather than optimally) over a wide range of potential scenarios even under future conditions that deviate from our best estimate [6].

The Info-Gap robustness function, Eq. (3), expresses the greatest level of robustness to uncertainty attained ($\hat{\alpha}$) for a target level of water deficit risk (r_c) by an adaptation strategy (q) over a range of potential future scenarios of supply and demand ($u \in U$). The scenarios are ordered by severity (Figure 1) and a most likely scenario of future supply and demand (ũ) is selected as a centralised point from which to begin the assessment. Adherence to the target level of risk is analysed for scenario ũ and then repeated for adjacent scenarios, branching out over a widening area of uncertainty (α). A risk of a water deficit value (R_d) is calculated for each scenario, Eq.(1), and must remain within the boundaries of $r_{c,}$ as stated by Hipel and Ben-Haim [7]. The Info-Gap assessment ends once no more adjacent scenarios satisfy r_c and the maximum robustness level ($\hat{\alpha}$) is calculated in reference to the robustness of water supply definition, Eq.(4).

$$\hat{\alpha}(q,r_c) = max \left\{\alpha: \max_{u \in U(\alpha,\tilde{u})} R_d(q,u) \le r_c\right\} \mathfrak{U} \tag{3}$$

$$\hat{\alpha}(q,r_c) = \frac{\sum_{u=\tilde{u}}^{U}(\alpha:\ R_d(q,u) \le r_c)}{\mathrm{U}} \tag{4}$$

The Enumeration method is applied to test all potential adaptation strategy combinations applicable to the region. This produces an array of adaptation strategies and their respective Info-Gap robustness levels. The total cost (NPV) of each adaptation strategy is calculated via Eq.(2), and then compared to the Info-Gap robustness levels to derive an optimum Pareto set.

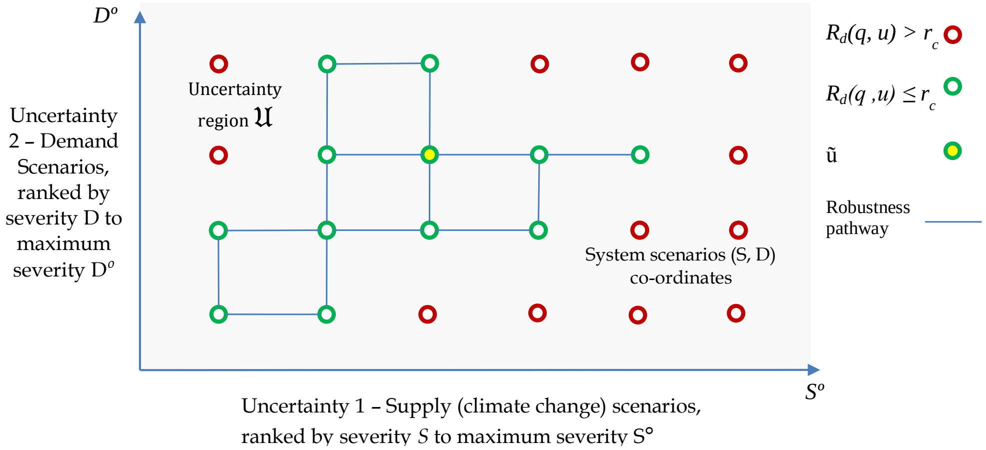

Figure 1. Info-Gap exploration of uncertainty region

In order to test the sensitivity of selecting a most likely scenario ($\tilde{u}$), three different starting locations have been selected across the uncertainty region. The starting locations correspond to the lower quartile, median and upper quartile in the ranked severity index, defined as $\mathrm{U}_{\mathrm{low}}$, $\mathrm{U}_{\mathrm{mid}}$ and $\mathrm{U}_{\mathrm{high}}$ respectively.

Method 2. Robust Optimisation (RO)

This Robust Optimisation (RO) method seeks to provide robustness in a 'global' context, in that it disregards attention to a local region of perceived higher likelihood and instead identifies the lowest costing adaptation strategies that provide a target level of robustness to a range of scenarios considered as discrete futures. RO involves the identification of a set of parameters that optimise to a set objective function (a goal), while abiding by a number of constraints [8]. For this IWRM problem the objective function is the minimisation of cost, the parameters are the adaptation strategies and the target level of robustness ($\bar{R}$) is the primary constraint which must be satisfied. Robustness is again calculated as the number of scenarios that keep to a target level of water deficit risk (r_c), however all scenarios are now examined free of localised constraints. Hence, if an 80% robust water supply is the target then the adaptation strategy that meets the target risk level over 80% of the scenarios for the least cost is identified as the optimal solution $\hat{q}$, Eq.(5).

$$\hat{q} = \min_{q \in Q} NPV_q \left\{ \frac{\sum_{u=1}^{U}(R_d(q,u) \le r_c)}{U} \ge \bar{R} \right\} \tag{5}$$

This identifies the optimal low cost strategies for changeable levels of target robustness. The Enumeration method is used to analyse all potential adaptation strategies for varying target robustness's $\bar{R}$ and ultimately identify the Pareto optimal set of results.

CASE STUDY

The decision making methods IG and RO were applied to a case study of Southern Waters: Sussex North Resource Zone (SNRZ); a region in the South East of England that has been listed by the Environment Agency in 2007 as under “a severe level of water stress” [9].

Figure 2. Southern Water: Sussex North Resource Zone (highlighted)

The existing water resources for the SNRZ system are shown in Table 1. Water from all sources is treated at the Hardham Water Treatment Works (WTW). Baseline demand, as of 2010 [1], was 67.57 Ml/d Dry Year Annual Average (DYAA).

Table 1. SNRZ existing water sources

Resource	Resource Description	Minimum Deployable Output (MDO) In Ml/d	Projected to be affected by climate change?
A	River Rother Abstraction	40*	Yes - significantly
B	Groundwater Sources	11.05	Yes - moderately
C	Weir Wood Reservoir Storage	21.82	Yes - moderately
D	Transfer from Portsmouth Region	15	No
E	Reserve Groundwater at Hardham	36.96*	Yes - moderately

*Dependent on minimum residual flows in the river Rother (MRFs)

An investigation into new water supply resources was carried out using data surveys run on the Sussex North Region [1][10]. This created a list of potential individual resource options with which to form the adaptation strategies. These options varied from a new pipeline to help refill Weir Wood reservoir, capable of providing around 3 ML/d (MDO) additional water supply for approx. £3.2 million, to a new large dual fed reservoir costing upward of £47.8 million and providing approx. 26 Ml/d. UK water companies typically use a 25 year planning horizon in their WRMPs however; a time horizon of 50 years has been selected for this study to include the longer term impacts of the changing climate. Risk assessment is carried out on a daily time step from 2015 to 2064, utilising the water supply model created in Python. Future scenarios have been developed which include the impacts of climate change on the region’s supplies and take account for the impact of population changes on future demand.

Supply Scenarios

The future supply levels in the region were projected by applying Future Flow scenarios to the major contributing rivers and reservoirs in the region. The Future Flow scenarios were produced by the Centre for Ecology and Hydrology [11] and they provide 11 plausible realisations of the river flows at various river gauging stations across England, Wales and Scotland and account for the impact of climate change to 2100 under a Medium emission scenario. Any data required downstream of a gauging station were extrapolated using a flow factoring method which perturbs the historic river flow data to match the flow changes at the upstream gauge. To allow for different natural variability the 11 Future Flow scenarios are resampled [12] in seasonal blocks to produce additional future river flow scenarios. In total 72 discrete supply scenarios were formed.

Demand Scenarios

Demand Scenarios for the Sussex North region have been produced using data from Southern Waters Water Resource Management Report (WRMP) 2010-35 [1]. They consist of 4 scenarios based on varying success levels following the enforced introduction of Universal Metering in the region. This requires full metering of all properties and non-household businesses by 2015 and the scenarios illustrate the projected effect of this introduction from a pessimistic demand increase to more optimistic results and also including scenarios of low leakage increases and high leakage increases.

Target Level of Water Deficit Risk

When evaluating the adaptation strategies over the future supply and demand scenarios the aim is to maintain the water supply system at the same level of acceptable risk as the baseline historic period [1]. The water deficit risk (r_c) was determined by simulating the present day water supply configuration between (1956-2005) resulting in the system risk of 0.425 Ml.

RESULTS AND DISCUSSION

For each decision making method the 72 supply and 4 demand scenarios (i.e. a total of 288 possible combinations) were modelled with the adaptation strategies, which are assessed in accordance to objective functions subject to each method's individual constraints. This led to the identification of Pareto sets for both decision making methods, trading-off the robustness of water supply and cost of adaptation strategies (Figure 3).

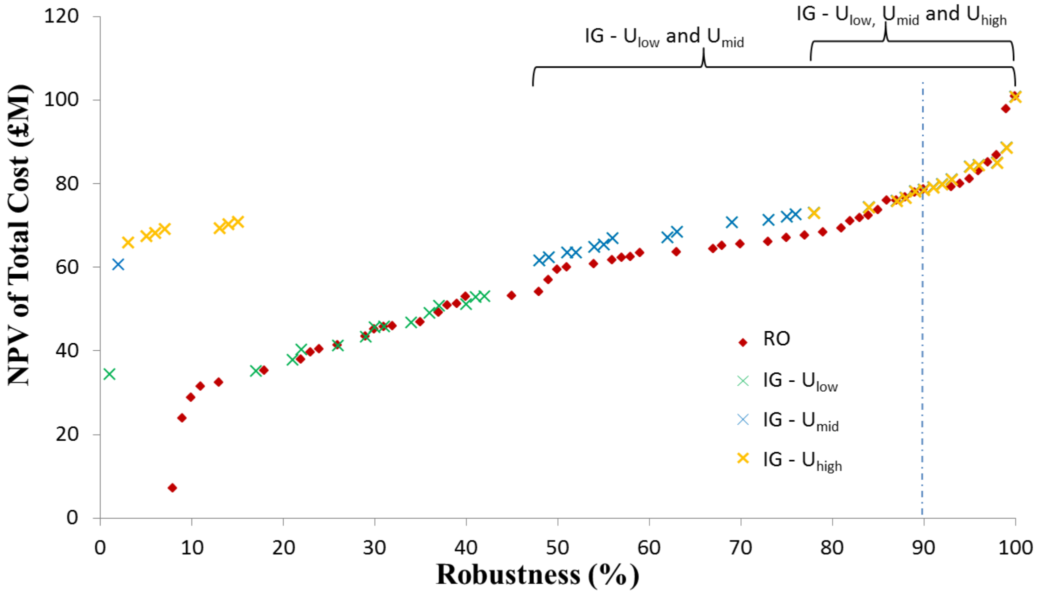

Figure 3. Pareto sets identified by the IG and RO methods

As it can be seen from Figure 3, the IG method produces the higher costing strategy recommendations than the RO method for robustness's below 90% when the starting point $\tilde{u}$ is set at U_{mid} or U_{high} in the severity index (blue and yellow crosses in Figure 3). This is due to the IG method examining the uncertainty region from a local point outwards, leading to more stringent risk reduction requirements than those placed on global robustness. This is especially apparent when $\tilde{u}$ is set at U_{high} as this places the most severe scenarios (e.g. decreasing supply and increasing demand) that must be satisfied in close proximity to the starting point. The IG method with $\tilde{u}$ set at U_{low} produced very similar Pareto strategies (green crosses in Figure 3) to that of the RO method in the region of low robustness (<45%). This is due to the lower levels of robustness requiring a smaller proportion of the uncertainty region to be covered coinciding with the less severe scenarios in the proximity of U_{low}, reducing the potential of premature breaking of the IG 'pathway'. This allows a greater range of strategies to satisfy the robustness level, leading to more similarities in the optimums produced. All Pareto fronts converge above 90% robustness, marked as the point at which the differences in the constraints of local and global robustness become negligible. The larger gaps in Pareto coverage for the IG method, especially identified for U_{mid} and U_{high} fronts, is due to the occasional large increases in risk reduction required for individual scenarios when they are ordered by a severity index that is not monotonically increasing. This highlights the difficulty in ordering discrete scenarios into a range of severity and presents a potential weakness in the IG method in application to IWRM.

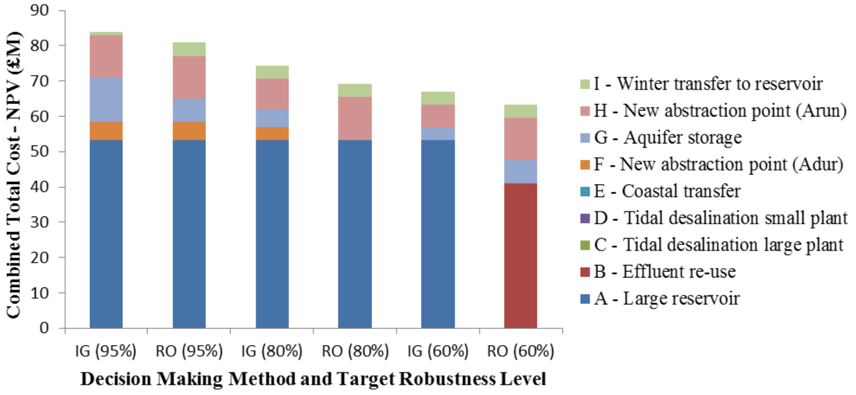

Figure 4. Components of Pareto strategies at varying target robustness levels (RO and IG-U_{mid})

Figure 4, presents the adaptation strategy components for optimal solutions under robustness levels of 95, 80 and 60 percent respectively for RO and IG (U_{mid}). Several individual water resource options are highlighted as being prime cost effective options following their selection by both methods (e.g. Option H). Despite this the optimal strategies vary considerably in total cost with RO identifying strategies an average of 8% cheaper than IG (U_{mid}) for 50-80% robustness levels reducing to a negligible difference from 80-100%.

Table 2, shows the performance of the six strategies from Figure 4 in terms of their associated risk calculated across all scenarios, examining; maximum risk, average risk and maximum risk regret (the risk reduction lost by selecting some strategy over another). The highlighted results are the best performing method at each target level of robustness, distinguishing IG as producing the more expensive but generally more risk averse strategies, until the convergence of the Pareto sets at 85-90% robustness levels. This trades-off an increased risk reduction to the water system for marginally increased costs.

Table 2.Risk performance factors for optimum strategies (RO and IG-U_{mid})

Method	Cost (£ Millions)	Max Risk (Ml)	Average Risk (Ml)	Max Regret (Ml)
IG (95%)	83.9	12.7	0.15	7.1
RO (95%)	**80.9**	**5.6**	**0.09**	**0.39**
IG (80%)	74.4	**20.3**	**0.72**	**0.01**
RO (80%)	**69.2**	102	2.14	81.7
IG (60%)	67.0	**77.8**	**2.56**	**0.01**
RO (60%)	**63.4**	142.2	4.22	72.1

CONCLUSIONS

Both IG and RO show potential in water resource adaptation planning, however they are highly debated methodologies [13] due to their global vs local handling of uncertainty. The IG method is appropriate providing high confidence can be placed in the most likely range of projections selected. This can tailor robustness around the most probable scenarios, which can be seen as positive or negative depending on the level of confidence in the projections. However, if a high level of robustness is required then both methods provide similar results, as seen by the convergence of the Pareto fronts on Figure 3. The very concepts and perceptions of robustness and of risk need to be further examined on supplementary case studies in order to better ascertain the benefits of the different methods. Further work will also include evaluations of additional decision making methods as well as introducing innovative concepts and considerations of additional trade-offs such as energy, environmental and social factors.

REFERENCES

[1] SW, Southern Water., "Water Resources Management Plan, 2010-2035" – Main Report, Southern Water, UK, (2009)

[2] EA., "Water resources planning guideline: The technical methods and instructions", Development by Environment Agency, Ofwat, Defra and the Welsh Government (2012)

[3] NERA., "The Economics of Balancing Supply and Demand", National Economic Research Associates – Main Report, London. http://www.nera.com (2002)

[4] EA., "Water Resources Planning Guidelines"; http://environment-agency.gov.uk/business/sectors/39687.aspx (2008)

[5] Ben-Haim Y., "Info-Gap Economics: An Operation Introduction". Palgrave Macmillan, Basingstoke, (2010).

[6] Ben-Haim, Y., "Decision Trade-offs Under Severe Info-Gap Uncertainty", 2nd International Symposium on Imprecise Probabilities and Their Applications, Ithaca, New York, (2001).

[7] Hipel K.W., Ben-Haim Y. "Decision Making in an Uncertain World: Information-Gap Modelling in Water Resources Management", IEEE Transaction on Systems, Man, and Cybernetics Part C: Application and Reviews, Vol 29, No. 4. (1999), Pp. 506-517.

[8] Beyer H.G., Sendhoff B., "Robust Optimisation – A Comprehensive Survey". Computer Methods in Applied Mechanics and Engineering 196(33-34), 3190-3218 (2007)

[9] EA., "Areas of Water Stress: final classification", EA, Rio House, Bristol, (2007).

[10] Atkins., "Sussex North Water Resource Investigation, Phase III Options Appraisal Report", Atkins plc, Epsom, Surrey, (2007).

[11] Prudhomme C., Dadson S., Morris D., Williamson J., Goodsell G., Crooks S., Boelee L., Davies H., Buys G., Lafon T., "Future Flows Climate", http://dx.doi.org/10.5285/bad1514f-119e-44a4-8e1e-442735bb9797. (2012).

[12] Ledbetter R., Prudhomme C., Arnell N., "A method for incorporating climate variability in climate change impact assessments: Sensitivity of river flows in the Eden catchment to precipitation scenarios", Climate Change, Springer Science, Business Media, B.V, vol. 113, issue 3, (2012), pp 803-823.

[13] Sniedovich M., "The Art and Science of Modelling Decision-Making Under Severe Uncertainty", Decision Making in Manufacturing and Services, 1, (2007), pp 111-136.