**Structural Optimization: LBR-5 Software and Application to a Mega Yacht [Title: Times New Roman, Bold, Size 14, Line space 1.5]
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**Abstract [Times New Roman, Bold, Size 12, Line space 1.5]**

The complex and multidisciplinary nature of ship design **[Times New Roman, Size 11, Line space 1.5]** together with the requirement to examine life-cycle characteristics, compels to incorporate uncertainty since the first phases of ship design process. Especially, concept ship design is the stage mostly characterised by imprecision, uncertain parameters, and ill-defined relationships. A short tutorial is presented on the Method of Imprecision (MoI), a formal theory for representing preferences among design alternatives by incorporating imprecise information into design process by means of the mathematics of fuzzy sets. The MoI formulates the concept design of ships as a Multi Attribute Decision-Making (MADM). The underlined strategy is to let the design team select from a variety of overall preference combinations among attributes. A Ro-Ro concept ship design example indicates how the MoI may be applied to assess imprecision of basic data.

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**Keywords:** Ship Design, Fuzzy Sets, Imprecision**,** Preferences, Aggregation Functions

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## 1. Introduction [Section: Times New Roman, Bold, Size 12, Line space 1.5]

Aspirations for the conquest of new markets are **[Times New Roman, Size 11, Line space 1.5]** higher than ever as new technologies and global competition compel to introduce intelligent synthesis since initial stages of ship design. Hence, dramatic changes are needed in how ships are designed, produced, operated, and maintained. As a result, it is mandatory to develop designs that are as less sensitive as possible to prediction inaccuracies without suffering for reduced performance and economic penalties.

In general, the concept ship design is a critical task in the design process, since the most important decisions with the greatest impact on ship’s overall economic efficiency are made there **[To give a reference in the text, place only the authors’ last name and the date of publication in parentheses.]** (Grubišić et al., 1990). Concept design is a very complex activity, even if it has simply to provide preliminary sizing of a ship that has to provide the payload/deadweight and speed expected by the shipowner at a minimum RFR. The complexity lies on diverse sources of technical, physical and economic issues to process and balance simultaneously according to a prescribed set of criteria (functional requirements, operating constraints, and evaluation attributes). Moreover, this very initial design stage is the most risky since the ship description is still incomplete and *imprecise* (fuzzy), while associated with multiple, interacting, and conflicting constraints that are often of doubtful formulation and formalisation. Insufficient robustness in the concept design phase is the major cause of failure for most of the upstream life-cycle engineering products (Salzberg and Watkins, 1990).

In modelling the concept ship design, deterministic ‘black boxes’ are usually used to assess attributes that cannot be determined exactly due to vagueness of many parameters. A further critical point is that the uncertainties of one attribute may be propagated to another one through the linking of design variables so that there could be an accumulation of uncertainty from different individual disciplines. Therefore, it is mandatory to develop a methodology to represent and incorporate imprecision since concept design stage to facilitate the ship designers in the decision-making process. Even MADM techniques, in spite of allowing multidisciplinary control of many variables and criteria, still remain of academic interest only, if computations and decisions are purely deterministic based. To overcome these limitations, Trincas et al. (1994) introduced robustness in concept ship design. But further extensions are required.

This paper shortly reviews the so-called *method of* *imprecision* (MoI) for concept ship design in the framework of MADM. A case test is presented to illustrate how the MoI may be applied to an imprecisely specified ro-ro concept design problem.

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**2. The Method of Imprecision [Section: Times New Roman, Bold, Size 12, Line space 1.5]**

The MoI is a set-based approach which uses the mathematics of fuzzy sets to include imprecise information in the design description and uncertainty in requirements, both relevant to decision making. It helps the design team to represent preferences among alternative designs, thus supporting robust decision making which is still based on deterministic evaluation models from various technical and economic disciplines. In designing, imprecision means uncertainty in selecting among alternatives.

Unfortunately, in evaluating and ranking a set of alternative designs, performance attributes are usually incommensurate (speed, weight, power, comfort, cost, etc.). A traditional approach to combining such incommensurate attributes is to use normalisation and/or weighting sum techniques, thus requiring both a conversion of units, and a measure of relative importance of the individual attributes. On the contrary, in the MoI preference information on the design variables and performance attributes are combined into an overall preference rating for the non-dominated set of design solutions.

In the MoI, the preferred statements for design variables and performance attributes are represented using fuzzy sets, by constructing a scale converting the preferential statements between zero (totally unacceptable) and one (completely acceptable). The result is the formal calculation of an overall preference *m*0  [0, 1] for each candidate design.

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**2.1. Fuzzy Definition of Design Parameters [Sub-section: Bold, Size 11, Line space 1.5]**

Fuzziness in ship design stems from the imprecise nature of prediction methods. As compared to crisp requirements, fuzzy approach softens the sharp transition from feasible to unfeasible (Zadeh, 1978). It may identify an optimal solution that is close to the infeasible region and which would otherwise be lost by crisp constraint criterion. At the same time, the values of design variables, parameters, and attributes should be normalised in order to make them commensurable in a multidimensional space. Although other design methodologies do exist that implicitly represent imprecision and uncertainty, fuzzy design methods were found very useful in ship design (Shinoda and Fukuchi, 1991).

A fuzzy set *X* is defined as the ordered set of pairs [*x, m*(*x*)] in which *x* denotes an element in the fuzzy set*,* while **(*x*)represents the membership grade that *x* has in the fuzzy set*.* To assess designers’ preference on the value of specific attribute, different types of *membership grade function* may be used.**The higher the value of **, the higher the confidence in the design variable and/or the dependent design response.

Many formulations of membership grade are possible but generalised Nehrling-type function (1985) was found most suitable for application of fuzzy logics in concept ship design:

 **[Equation aligned left, Equation number aligned right]** (1)

The values to *x*\*, *d*, and *n* may be selected so that ** can measure the aspiration level of the design team for specific attribute. Four types of membership grade function are possible: ascending (S-type), descending (Z-type), attracting (-type) and averting (U-type). Therefore, it is mandatory to develop a methodology to represent and incorporate imprecision since concept design stage to facilitate the ship designers in the decision-making process. A traditional approach to combining such incommensurate attributes is to use normalisation, thus requiring both a conversion of units, and a measure of relative importance of the individual attributes. Two points on a membership grade curve are important, namely,

1. *x* = *x*٭, that is, the level of attribute that is 100% satisfactory, i.e. the level that may optimistically be expected to be reached by the best design as to specific attribute.
2. *x* = *x* 0.5 = *x*٭ – *d*, that is, the level that is only 50% percent satisfactory, i.e. the level that may be expected in the average design.

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**3. Computation of Preferences [Size 12]**

The design preferences, ’s, are specified in the *DS* and can be aggregated into the combined design preference . In similar way, the performance attributes, ’s, are specified in the attribute space and can be aggregated into the combined functional requirements. These combined preferences have to be in the same space in order to aggregate them into the overall preference for a design,; usually the mapping from *DS* to *AS*. As is computationally expensive,  can be replaced by its metamodel  to reduce the computational cost.

Limits of acceptability for range of variables are familiar to naval architects. Such acceptance ranges correspond to intervals over which preference is greater than zero. This suggests that rather than determine the preference *d* at each value of *di* , it may be more natural to determine the intervals in *di*,

 (2)

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**4. Case Study**

The following case study shows how a deterministic design mathematical model can be integrated with the MoI in a MADM suite. The problem used in the example is the concept design of a fast Ro-Ro ship. There are five independent variables to represent the candidate designs (*d*1 = length, *d*2 = beam, *d*3 = draft, *d*4 = amidships coefficient, *d*5 = longitudinal prismatic coefficient, *d*6 = vertical prismatic coefficient) and six performance attributes (*a*1 = service speed, *a*2 = number of cars, *a*3 = number of trailers, *a*4 = required freight rate, *a*5 = acquisition cost, *a*6 = motion sickness incidence). The range supports with **-level cut equal to zero are given in Table 1.

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**Table 1.** Intervals of design variables **[Centered, Size 10, Paragraph After=4 pt]**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Design variable | *d*1 | *d* 2 | *d* 3 | *d* 4 | *d* 5 | *d* 6 |
| Minimum value | 184.00 | 23.80 | 6.40 | 0.900 | 0.610 | 0.590 |
| Maximum value | 200.00 | 32.25 | 7.40 | 0.950 | 0.640 | 0.710 |

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About 3,000 feasible designs were generated by an adaptive Monte Carlo method. The membership grade function given by equation (1) was used to evaluate the satisfaction-to-target achieved for each attribute. The membership grade function given by equation (1) was used to evaluate the satisfaction-to-target achieved for each attribute. After performing a Pareto-set filtering, the overall preferences for 97 non-dominated designs were calculated based on the aggregation function (4). There are five independent variables to represent the candidate designs. The target values and type of membership function associated to each attribute are tabulated in Table 2.

 **Table 2.** Target values and type of membership function for each attribute

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Attribute | *a* 1 | *a* 2 | *a* 3 | *a* 4 | *a* 5 | *a*6 |
| Target | 29.5 | 530 | 2300 | 2.10 | 92.5 | 10% |
| Type | S -type | -type | -type | Z-type | Z-type | Z-type |

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The design with the highest overall performance is *des\_37*, with  = 0.873. The point of highest preference is not far from the point of highest satisfaction achieved with the *min* operator (1).

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**Fig. 1.** The **-cuts of ship length at given overall preferences

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**Fig. 2.** The **-cuts of ship beam at given overall preferences

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The overall **-cuts  of the most influencing variables (as derived from statistical analysis of metamodels) were then identified from Figures 1 through 4; they are reported in Table 3.

**Table 3.** Design variables of the extreme designs at given overall preferences

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Cut level | *LBP*min max | *B*min max | *CP*min max | *CVP*min max |
|  = 0.75 | 193.57 200.59 | 26.09 27.45 | 0.6275 0.6381 | 0.6120 0.6617 |
|  = 0.80 | 194.18 199.62 | 26.21 27.37 | 0.6289 0.6371 | 0.6165 0.6552 |
|  = 0.85 | 194.74 198.77 | 26.33 27.28 | 0.6304 0.6360 | 0.6218 0.6486 |

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The fuzzy set design based on the fuzzy **-cut technique allows to measure uncertainty related to each design variable. Here, uncertainty is intended as the ratio of the **-level support to the value of the design variable of the design for which the overall induced preference reached the maximum value; in the case study, the best possible design is the ship designated by *des\_37*. The derived uncertainties ** of the main variables for three **-cut levels are given in Table 4. It can be seen that the less uncertain design variable is *CP* , whereas the most uncertain is *CVP* which is a hull geometric characteristic influencing ship vertical motions dramatically. This conclusion is consistent with the large spread of motion sickness incidence (*a*6) outcomes in the Pareto-set.

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**Table 4.** Uncertainty for the **-cut technique

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| -cut | *LBP* | *B* | *CP* | *CVP* |
| *supp* | ** | *supp* | ** | *supp* | ** | *supp* | ** |
|  = 0.75 | 7.020 | 0.0354 | 1.360 | 0.0499 | 0.0106 | 0.0128 | 0.0497 | 0.0771 |
|  = 0.80 | 5.440 | 0.0274 | 1.160 | 0.0426 | 0.0082 | 0.0107 | 0.0387 | 0.0600 |
|  = 0.85 | 4.030 | 0.0203 | 0.950 | 0.0349 | 0.0056 | 0.0088 | 0.0268 | 0.0416 |

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It is interesting noticing that the successful fast ro-ro designed and built by Fincantieri shipbuilding company for Minoan shipping company reaches the overall preferences given in Table 6.

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**Table 6.** Induced preference for the Minoan fast ro-ro/car/pax vessel

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Dimension | *LBP* = 194.0 m | *B* = 26.4 m | *CP* = 0.630 | *CVP* = 0.650 |
| ** | 0.782 | 0.871 |  0.844 |  0.843 |

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**7. Conclusions**

The goal of modern engineering design is to increase the amount of information available to designers regarding the performance of design alternatives, over that available with conventional design analyses. The effects will be greater, the earlier the information is made available. The most important and costly decisions in the design cycle are made in the concept design stage where ship performance is represented imprecisely. Capability to represent and manipulate imprecise descriptions of ship design there will enable decisions to be made with greater confidence and reduced risk.

To this end, the technique used here is a MoI approach operating on fuzzy representations of design parameters. Preference functions are used to represent the designers’ aspiration to arrive at desired levels of attributes. The class of product of powers for the aggregation of these preferences was utilized in this paper. The case study demonstrates that it provides the ability to manage uncertainty in selecting the ‘best possible’ design even if ship’s attribute outcomes are assessed starting from a variety of imprecise variables. It has been shown that the imprecise result derived through a MADM approach including the MoI provides more information than conventional single-valued design analysis.

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**[For all reference items: List in alphabetical order with respect to author surnames. Only author names are bold, Times New Roman, Size 10, Line space 1, Paragraph After 8 pt]**