TOWARDS TESTING AND VALIDATION OF NOVEL CONCEPTUAL PROCESS DESIGN FRAMEWORKS

Augustine N. Ajah, Pieter L.J. Swinkels* and Johan Grievink.
Process Systems Engineering Group, Delft University of Technology
Julianalaan 136, 2628BL Delft, The Netherlands.

Abstract

Effective design procedures contribute to meeting the increasing societal demands for high(er) plant performance and shorter time to market by goal driven process development. The place of systematic design frameworks in such design procedures has been recognized and consequently resulted into developments of systematic, hierarchical and multi-space design frameworks. However, it is observed that not much is known in the process design domains, of a systematic way of testing and validating such hierarchical multi-space design methods for the intended class of users. In this work a generic approach for the testing and validation of such novel design framework is being expounded. The study integrates the Analytical Hierarchy Process (AHP) and the Fuzzy Expert System (FES) to establish a concept for scientifically and quantitatively testing, analyzing, evaluating and validating novel design frameworks.

Keywords

Conceptual Process Design; Framework Validation Strategy; Fuzzy Evaluations in Design.

Introduction

In recent years, the area of conceptual process design has witnessed growing numbers of systematic design frameworks for handling the heavily constrained, complex and often difficult to master design activities. Contrary to this, no literature source could be found in this domain of any systematic method of testing and validating such multi-space design frameworks.

Given the paramount importance of the conceptual design stage on the overall design, it is emphasized that novel conceptual process design frameworks should be validated i.e. subjected to both internal and external checks of the correlation between the goals of the developed framework and the application effectiveness. This, achievable through applying such framework to real-life conceptual design activities, will not only provide a means of confirming the applicability of such a framework but will also offer critical feedbacks for its subsequent development and improvement.

The objective of this work is to develop a generic and systematic approach for the testing and validation of such framework. The approach comprises four stages, assuming that a candidate design framework has been selected for testing:

1. Specification of design performance criteria
2. Selection of design teams and cases
3. Testing and monitoring of design process
4. Evaluation of design outputs

These stages as well as the results from an application are presented below. A novel design framework developed by the authors (Ajah et al., 2003), comprising a hierarchy of task-oriented design spaces, with an explicit consideration of the generic design steps (synthesis, analysis, evaluation) in each space, is applied to a real-life technology case.

* To whom all correspondence should be addressed

Specification of Design Performance Criteria.

The relevant performance criteria for the evaluation of the design cases were developed in line with the Plant design Improvement through Quality Review (PIQUAR) principles, (Herder, 1999). The developed design performance criteria are as shown in *Table 1*. An independent Design Expert Panel (DEP) consisting of seven experienced designers from both academia and industries alike ranked these performance criteria, using the Saaty Analytical Hierarchy Process (AHP) (Saaty, 1982).

Selection of Design Teams and Cases

The optimum means of validating any design framework lies in the application of such framework to a real-life industrial or academic conceptual design problem. Therefore, designing the environment (industrial or academic), the class of test and control designers (experienced or in-experienced) as well as the choice of the technological case (complex or simple, continuous or batch) is the second stage to be encountered in such validation exercise.

One of the envisaged drawbacks in the selection of the design teams and cases is that it may be practically difficult for industries to endorse the use of such tentative design framework on any of their live-design projects or for such framework to be enthusiastically accepted for application by experienced practicing designers in the often high-pressure work environment. Although, the preliminary test was conducted in an academic environment (owing to the above hitches) and by relatively in-experienced design teams of M.Sc. Chemical Engineering students (Design Cases A & B), it is the authors' supposition that the results should be more or less the same when applied at the industry level. The design outputs were compared with those produced by a control team of more experienced post-graduate designers (Design Case C) for the same technology case. However, for statistical relevance, more than two tests should have been ideal but for time constraints and unavailability of any clearly developed method for such a test, the test cases was narrowed to two.

For the real live technology case, *the conceptual design of a Gas-to-Liquid Fischer Tropsch Synthesis plant* was adopted because of its considered importance in the future energy industry.

Testing and Monitoring

The third cardinal stage is the testing and the monitoring of all the design activities during the design process. This, apart from affording the opportunity of gaining a first hand knowledge of the intrinsic work flow pattern of the design framework, also offers the possibilities of identifying the gray areas in the framework. During the testing and monitoring some of the variables of interests such as the actual amount of design time used in each design space and in each generic design phase of the framework, the work flow patterns etc were captured through thorough activity logging.

Evaluation of Design Outputs

The last stage is the analysis and evaluation process of the product data (design outputs). The independent Design Expert Panel (DEP) also critiqued the design outputs. The evaluation of the outputs of the test designs had to be compared with the control design output or any other standard that may be set as metric for the evaluation using the AHP. However, since most of the information and data, available for the evaluation and subsequent validation of design frameworks at this stage are usually not all quantitative and well defined, the Fuzzy Expert System (Zadeh, 1965) was employed for the integration of the objective and subjective information and data in the evaluation of the design outputs.

Table 1. Developed design performance criteria

Performance Criteria		Performance Criteria	
Economics		**Documentation**	
1	Economic viability	11	Design report organization
Technical Feasibility		12	Process/equipment alternatives
2.	Safety & environmental benignity	13	Design Decision /Rationale
3	Operability	14	Intermediate Results
4	Availability	**Work process**	
5	Simplicity of design	15	Creativity
6	Product quality and quantity	16	Design Problem Definition
7	Heat/material integration	17	Concurrency
8	Feasibility of start up & shut down	18	Design Time Reductions
9	Innovativeness	19	Basis-of-Design implementations
10	Sustainability	20	Domain knowledge acquisition & application

Evaluative Analytical Hierarchy Process (AHP)

This involves the weighting of the developed performance criteria in terms of their perceived degree of importance and subsequently all the design cases are then weighted according to each criterion using a set of Pairwise Comparisons (PC). In this work, all the assignments of weights were done by the DEP and an averaged weight taken as a consensus weight. These weight ratios were derived from the nine discrete importance scales propounded by Saaty. Surprisingly, the experts' weightings were more or less the same.

The normalized weight vector for all criteria per expert (k) equals the first eigenvector of a pairwise comparison matrix (using MATLAB®),

$$\overline{w}^{(k)} = [w_1, w_2, \cdots, w_n]^T \quad (1)$$

The performance of a design case (i), D_i, is formulated as a weighted, linear additive function over expert weights (k) and their rating of the design, $X_{ij}^{(k)}$, with respect to criteria (Cj):

$$D_i = \frac{1}{K}\sum_{k=1}^{K}\sum_{j=1}^{n}\overline{w}_j^{(k)} X_{ij}^{(k)}, \forall i = A, B, C \quad (2)$$

Fuzzy Evaluation of the Design Cases

As stated earlier, estimating the performances of given design cases using the AHP, can be influenced and /or limited by a number of factors and uncertainties. In order to deal with these limitations the fuzzy expert system, which converts these linguistic terms into a specific fuzzy number (membership function), thus allowing a trade off analysis among the various criteria to be performed, might offer an alternative and has been applied in this work.

Steps in the Fuzzy Evaluation

The first three steps (design of design cases, criteria development and weighting) of the fuzzy evaluation have been treated in the AHP method. The last three steps of the fuzzification exercise are described below.

Converting Linguistic terms into Fuzzy Numbers (Fuzzification)

Fuzzification is a process of converting linguistic terms or crisp numerical values into the degrees of membership these values have in the fuzzy sets. Such grade of membership μ(x) arbitrarily ranges from 0 to 1 for non-membership and membership respectively. Other intermediate values are possible as well. The method of Chen and Hwang (1992) for converting linguistic terms into fuzzy numbers based on triangular fuzzy representations was adapted for this work.

Lumping of Criteria (Fuzzy Composite Programming)

The Fuzzy Composite Programming (FCP) is a step-by-step manual procedure for regrouping a set of basic criteria to form a single performance indicator based on which, the design cases will be finally assessed, (Bogardi and Bardossy, 1983). There are virtually, three levels of the FCP as shown in *Figure 1* .At the first level are all the individual performance criteria denoted by $C_1i - C_ni$ for all the first level economic related performance criteria, and $C_1j - C_nj$, $C_1k - C_nk$ and $C_1l - C_nl$ for all the first level technical feasibility, documentation, and work process related performance criteria respectively as listed in Table 1. These form the second level performance indicators, economics (**EC**), technical feasibility (**TF**), documentation (**DOC**) and the work process **(WP).** The second level indicators are lumped into the final Design Improvement Index (**DII**) in the third level of the FCP. The design case with the highest **DII** is regarded as the best design and the novel framework under test is validated if its overall performance equals or outranks a set standard.

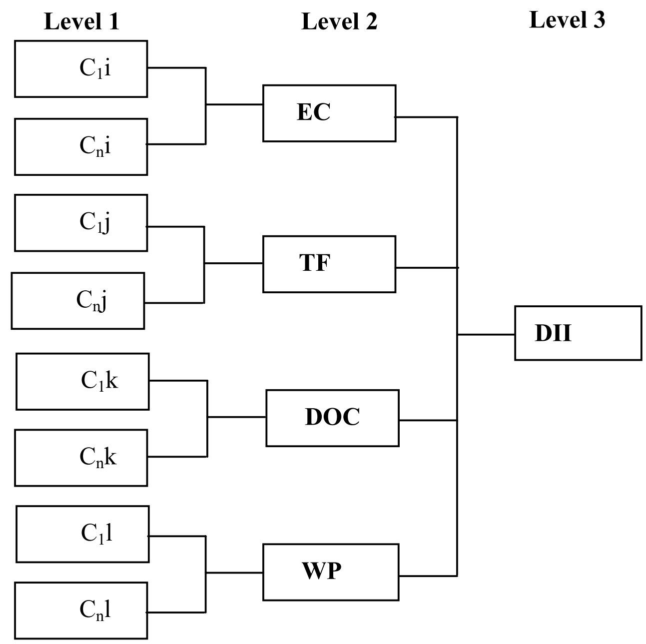

Figure 1. Lumped (Composite) evaluation criteria

Fuzzy Ranking of the Design Cases

TOPSIS-Technique for Order Preference by Similarity to Ideal Solution (Hwang and Yoon, 1981) was used in the ranking of the resulting triangular fuzzy plots. Using this approach, the best design case is the one, which has the shortest distance to the ideal solution. The ideal solution lies at point (1.0, 1.0), the black rectangular point in figure 5, (Khan et al., 2002) with respect to the membership function and fuzzy number.

Results and Discussion

The work process analysis shows that a striking **43%** reduction in total design time was realized using the novel design framework being tested. This large time reduction might be explained by the sequential-parallel work progression initiated using the framework, in contrast to the conventional sequential approach. Design Space 4 (physical-chemical tasks architecture) consumed the highest design resources (approx.25%) in Design Cases A & B. This shows that the current practice of quick short-circuiting into the equipment design stage by designers could be eliminated using this design framework. In Figure 2 the AHP result of the three design cases is crisply presented, where Design Case A outperforms B and C on a normalized scale. Nonetheless, to verify the optimal design case amidst the evaluation uncertainties, the evaluation results are presented as fuzzy plots (Figures 3-5).

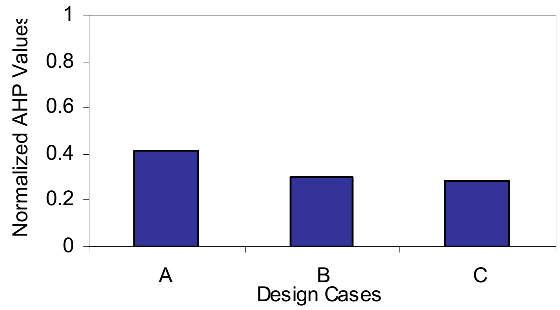

Figure 2. AHP Values of the design cases

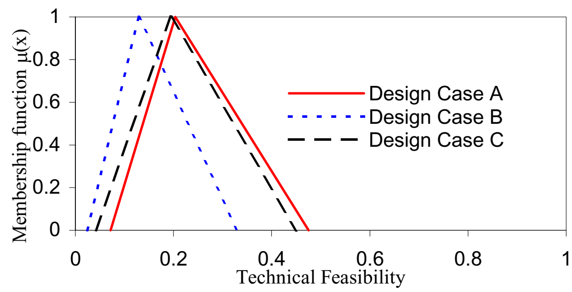

Figure 3. Fuzzy TF plot of the design cases.

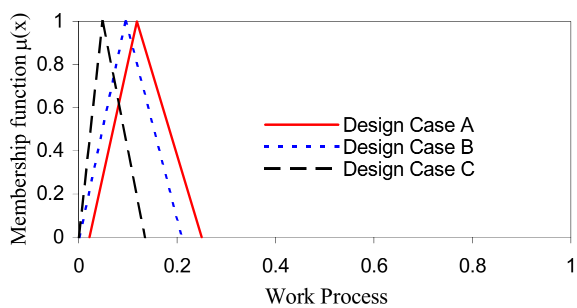

Figure 4. Fuzzy WP plot of the design cases

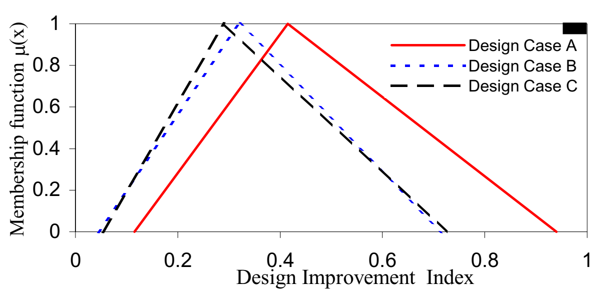

Figure 5. Fuzzy DII plot of the design cases

Figures 3 and 4 are representative second level fuzzy performance plots of the design cases. The DII, which is an agglomeration of the second level design performance indicators (EV, TF, DOC, and WP); add up to the systems index, the final basis for the design cases evaluation. The final design improvement index (Figure 5) reveals that Design Case A has the best overall design improvement performance. The performances of Design Cases B and C cannot be sharply discriminated since the distance of both to the ideal solution are almost same.

Conclusions and Future Work

A generic approach incorporating the AHP and the Fuzzy methods for the evaluation and subsequent validation of a conceptual design framework has been presented. To demonstrate this approach, it has been applied to a novel design framework, using a Fisher-Tropsch process as a design test case. The application of this generic approach in the testing and validation of a novel design framework reveals its (the design framework) feasibility and validity. The fuzzification of the crisp AHP results incorporated, reduced the imprecision often associated with the fact that most of the information and data available for the evaluation and subsequent validation of such design frameworks are usually not all quantitative and well defined. Both the AHP and the fuzzy results have a striking similarity, vis-à-vis the performances of the design cases. Nonetheless, accounting for the shortfalls identified earlier on, it is recommended that the number of design test cases be increased (for greater statistical relevance) and actual industrial tests of the concept be initiated.

References

Ajah, A.N., P.L.J. Swinkels, and J. Grievink (2003). Delft Design Matrix: A Framework for Conceptual Design of Future Process Plants. *Conf. Proceeding, Netherlands Process Technology Symposium -NPS3*, Veldhoven.

Bogardi, I., and A. Bardossy (1983). Application of MCDM to geological exploration.In Henson P., (ed), Essays and surveys on multiple criterion decision making. Springer-Verlag,New York.

Chen, S.H., and C.L. Hwang (1992). Fuzzy Multiple Attribute Decision Making, Springler-Verlag, New York.

Herder, P.M. (1999). Process Design in a Changing Environment; Identification of Quality Demands Governing the Design Process, Delft University Press, The Netherlands.

Hwang, C.L., and K Yoon (1981). Multiple Attribute Decision Making: Methods and Applications, Springler-Verlag, New York.

Khan, F.I., R. Sadiq, and T. Husain (2002). GreenPro-I: A Risk-based Life Cycle Assessment and Decision–Making Methodology for Process Plant Design, *Environmental Modeling &Software* **17**, 669-692.

Saaty, T. L., and L.G.Vargas (1982). The Logic of Priorities: Applications in Business, Energy, Health, and Transportation, Kluwer Nijhoff Publishing, Boston/The Hague/London.

Zadeh, L. (1965). 'Fuzzy Sets', *Information and Control*, **8** (3), 338-353.