*Artificial Intelligence for Engineering Design, Analysis and Manufacturing* (2000), *14*, 3–16. Printed in the USA.
Copyright © 2000 Cambridge University Press 0890-0604/00 $12.50

# Towards the support of innovative conceptual design through interactive designer/evolutionary computing strategies

I. C. PARMEE AND C. R. BONHAM
Plymouth Engineering Design Centre, University of Plymouth, Devon, UK
(RECEIVED March 10, 1999; ACCEPTED August 25, 1999)

**Abstract**

The paper discusses the requirements of the engineering designer during the higher, conceptual levels of the design process in terms of search within initial predefined design spaces and subsequent exploration of transformed design spaces. Such transformation is based upon information gathered from initial search using evolutionary techniques that rapidly identify high-performance regions of complex design spaces. It is proposed that off-line processing of such information and associated design team discussion in an iterative designer/evolutionary search procedure can strengthen the knowledge base relating to the problem at hand and initiate significant change in the design environment. Research relating to appropriate evolutionary search and exploratory procedures is described and illustrated with results from simple test functions and real-world design problems. These results support discussion related to the manner in which the techniques may best support innovative and creative design activity in an interactive design team/evolutionary search environment.

**Keywords:** Interactive; Evolutionary; Computation; Conceptual Design

## 1. INTRODUCTION

Although there is much evidence of the utilization of evolutionary and adaptive computing technologies for system optimization, there appears to be little recognition or investigation of their design exploration and search capabilities. Such capabilities support their appropriate integration with conceptual and preliminary design processes to support search within predefined design spaces whilst also allowing exploration in less well-defined areas that lie outside of initial constraint, objective and variable parameter bounds (Parmee & Denham, 1994; Gero et al., 1994; Parmee, 1997; Schnier & Gero, 1998). It is proposed that close individual designer and design team interaction with evolutionary and adaptive computing strategies can result in significant exploration involving off-line processing of initial results and related design information leading to a redefinition of the design environment. Such redefinition and further designer/evolutionary search may result in the discovery of innovative or even creative design solutions. Although not a definitive list, the following aspects must be considered if such integration is to be successfully achieved:

- the ability to efficiently sample complex design spaces described by differing model representation/simulation (e.g., quantitative, qualitative, linguistic, crisp, fuzzy, etc.).
- the addition, removal and/or variation of constraints, objectives and variable parameter bounds.
- the rapid identification of multiple high-performance solutions/regions of complex spaces.
- the development of search/exploration systems that can capture specific design knowledge through extensive designer interaction.
- the on-line processing of information relating to multiple design criteria concerning design, manufacturing, economic, and marketing requirements.
- the ability to access regions of design feasibility, to define such regions to some extent, and to identify optimal solutions within them.

Reprint requests to: I. C. Parmee, Director, Plymouth Engineering Design Centre, University of Plymouth, Drakes Circus, Plymouth PL4 8AA, UK. E-mail: iparmee@plymouth.ac.uk



https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

The importance of such aspects has become evident from recent research relating to the integration of evolutionary and adaptive computing with design processes (Parmee, 1998; Parmee, 1999*a*). Entirely machine-based evolutionary conceptual/preliminary design processes are not suggested here nor are they considered currently viable. The belief is that during conceptual design advanced computational search and exploration techniques can be utilized within a design team environment to support the engineer across a wide range of design activity and that best utility can be achieved by developing systems that enhance the inherent capabilities of the engineering designer. Experience suggests that successful integration can result in the development of prototype evolutionary design tools. These tools offer considerable potential providing powerful extensions to design team activity by allowing rapid, extensive exploration and stimulating innovative and creative reasoning at the higher conceptual levels of the design process. The paper describes one evolutionary strategy that supports such design exploration by providing an interactive, problem decomposition/transformation capability.

### 1.1. Evolutionary regional identification

During the higher, conceptual stages of design, evolutionary search strategies provide a capability to widely sample an initial predefined high-dimensional space leading to convergence upon optimal/high-performance solutions. Those variable parameters and other factors of the system under design that are initially considered to be significant describe this initial space. However, there is a requirement for exploration of alternative fitness landscapes through, for instance, the relaxation of variable parameter bounds, constraint penalties, and objective weightings. Although the initial objective of the evolutionary regional identification techniques described here has been the efficient decomposition of complex space, a longer-term objective is the development of highly interactive designer/machine environments that allow the on-line variation of conceptual design spaces. Such variation should lead to the discovery of areas of high potential outside of the initial design brief. A major aspect of interactive designer/evolutionary processes is the contribution to the development of the problem knowledge base during the early stages of design where poor definition and uncertainty are prevalent. This interactive development leads to the gradual redefinition of the design space through the:

- introduction/removal of variable parameters
- extension/reduction of the range of variation of such parameters
- introduction/removal of constraints
- softening/hardening of such constraints
- introduction/removal of objectives
- variation of objective weightings/preferences

In order to extract relevant information to support such interactive, iterative activity the following lower-level objectives must be achieved:

- good definition of high potential regions
- good set cover of each identified region in terms of number and diversity of solutions within them
- a minimization of number of calls to the evaluation (fitness) function
- robust strategies that perform well across differing problem domains
- succinct graphical presentation of extracted relevant, regional design information

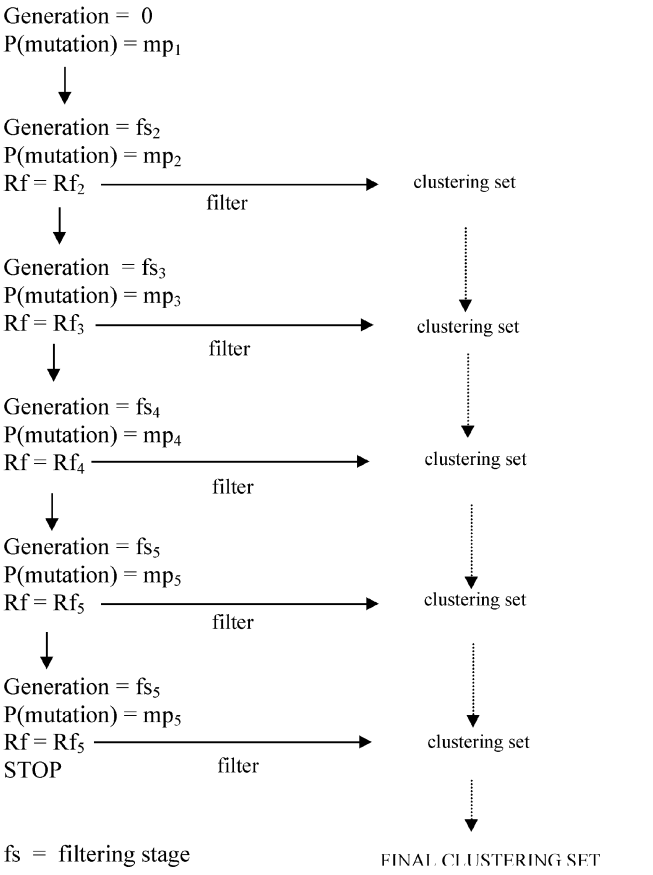
The following sections describe the development of regional identification strategies and techniques that satisfy these lower level objectives to some extent and their integration with a graphical user interface that currently represents a research prototype of an interactive design exploration tool. Graphical results illustrate the capabilities of the experimental systems on two-dimensional test functions and on a range of real-world problem types.

## 2. VARIABLE MUTATION CLUSTER-ORIENTED GENETIC ALGORITHMS (vmCOGAs)

The development of initial techniques (Parmee & Denham, 1994; Parmee, 1996*a*, 1996*b*; Parmee & Beck, 1997) concentrated upon the establishment of simple variable mutation regimes that encourage diversity during the early stages of a genetic algorithm (GA) (Goldberg, 1989) search and promote the formation of clusters of high-performance solutions. A high mutation probability is introduced at generation one and this is subsequently reduced at later preselected generations (filtering stages, $st_n$). The populations from these selected generations are extracted and passed through an adaptive filter. Those solutions that survive the filtering process are stored in a final clustering set as shown in Figure 1.

The adaptive filtering is a relatively simple process. It is assumed that the solutions from the extracted population are normally distributed and they are first scaled in terms of distance from the mean as shown in Figure 2. A threshold (Rf) is then introduced and solutions falling below that threshold are not allowed to enter the final clustering set. They do, however, remain within the GA population and contribute to the continuing evolutionary process. The filter's threshold value can also be reduced at each filtering stage to take into account the increasing overall fitness of the gradually converging populations. Solutions that exceed the threshold value of the previous stage in intermediate generations of the underlying GA are also passed into the final clustering set if they are not already present. This prevents loss of high-value information and improves set cover in the final clusters. Passing the populations through the adaptive filter avoids the requirement for *a priori* knowl-

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press




Populations at each filtering stage are extracted and passed through the adaptive filter. Surviving solutions are stored and allowed to enter the final clustering set which then defines existing regions of high performance.

**Fig. 1.** The vmCOGA topology.

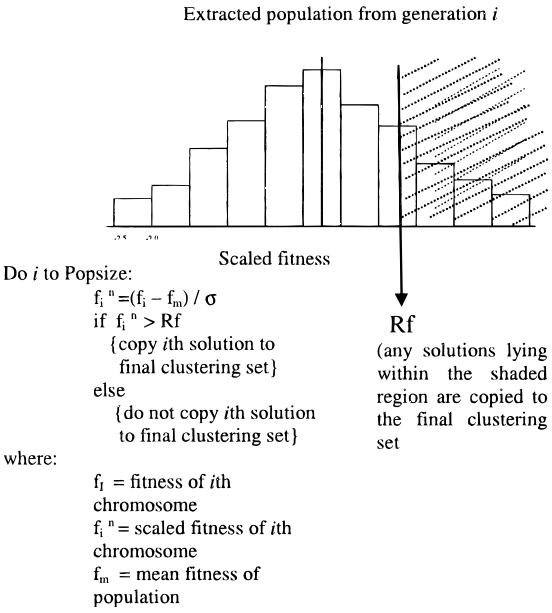



**Fig. 2.** The adaptive filter.

edge of the search space that is so often required for evolutionary multi-modal optimizers. The value of the Rf threshold of the adaptive filter is relative to known solutions describing the surface topography at a particular time, that is, at that preselected generation from which the population is extracted. The filter system therefore adapts to the information available thereby eliminating a need for *a priori* knowledge relating to the design space. The variation of the Rf values in consecutive runs can be utilized in an investigative manner to assess the relative nature of differing regions of the design space. Initial runs may have relatively low Rf settings to indicate general areas of the space containing solutions of above average fitness. Tightening of the filter threshold in subsequent runs results in the decomposition of this general area into succinct regions of high performance. The designer therefore accumulates knowledge not only concerning individual solutions or particularly high-performance regions but also of the relative nature of the surrounding space. This investigative process based upon Rf variation is illustrated in following sections. Further in-depth treatment of the development of the vmCOGA technique can be found in the referenced texts (i.e., Parmee, 1996*a*, 1996*b*; Parmee & Beck, 1997).

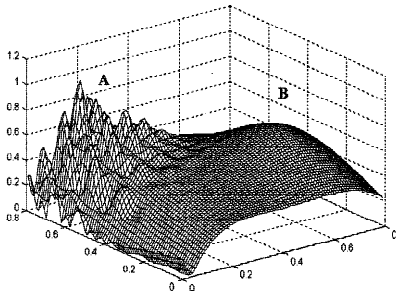
The COGA adaptive filter has also been integrated with a number of other evolutionary algorithms known for their explorative search capabilities (Bonham & Parmee, 1999*a*) and other exploratory search space sampling techniques have been introduced (Bonham & Parmee, 1999*b*). However, the results in following sections are all generated by vmCOGAs.

## 3. APPLICATION OF vmCOGA

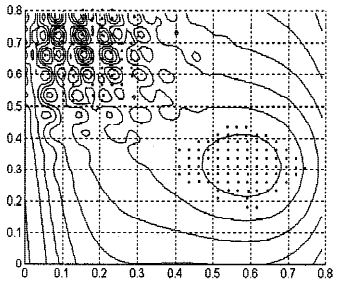
### 3.1. Two-dimensional test functions

Initial development of vmCOGA relied upon experimentation involving two-dimensional test functions to allow a visual assessment of the results through graphical representation in addition to a related set of quantitative criteria. This initial approach was essential in order to establish a basic understanding of problems relating to the achievement of the objectives concerning region definition, set cover, robustness, etc. Typical results from the application of vmCOGA to two of these functions are shown in Figure 3. The initial COGA concept arose from research relating to the integration of solution sensitivity with the fitness function in order to identify robust, high-performance solutions. Function one was developed to test COGA's ability to identify robust regions of a design space. Initial experimentation involving real-world high-dimensional problems relating to gas turbine design proved too complex to provide an indication as to best operators and operating regimes thus necessitating experimentation at these lower dimensions. However, research at this level has now re-

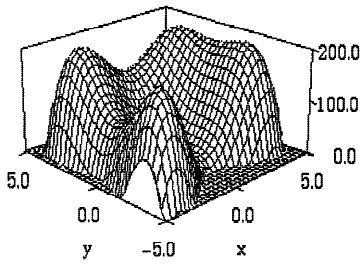
https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press



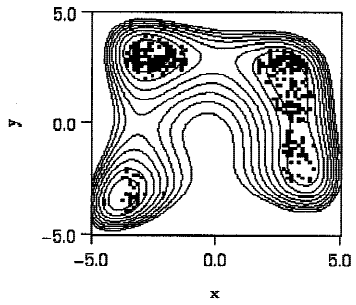

Surface plot of test function 1 with two distinct regions of high performance



Contour plot of test function 1 showing identified regions and region set cover




Surface plot of test function 2 with three distinct regions of high performance




Contour plot of test function 2 showing identified regions and region set cover

**Fig. 3.** Results of vmCOGA application to two-dimensional test functions.

sulted in a return to higher dimensional problems and research relating to scaleability issues.

### 3.2. Real-world application

The following sections illustrate the application of vmCOGAs in two higher dimensional design domains. The first relates to the preliminary design of military aircraft frames in collaboration with British Aerospace. This is a complex design domain characterized by uncertain requirements and fuzzy objectives relating to the long gestation periods between initial design brief and realization of the product (*circa* ten years). Changes in operational requirements in addition to technological advances in the interim cause a demand for a responsive, highly flexible strategy where design change and compromise are inherent features for much of the design period. The overall objective is the development of a high-performance machine that can outperform (in terms of many criteria) the opposition. In order to achieve this objective, design exploration leading to innovative and creative activity must be supported. The ability to introduce rapid change to satisfy the many operational, engineering, and marketing considerations as they themselves change is essential. British Aerospace utilize CAPS (Computer Aided Project Studies), a suite of preliminary design models developed in-house to support airframe design.

The research described here utilizes the miniCAPS model, a much abridged version of CAPS, for experimentation purposes. MiniCAPS retains major characteristics of the overall requirements however. Preliminary geometric definition, aerodynamic analysis, mass estimation, and performance analysis are included. Eight input variables generate up to eleven outputs relating to a range of objectives. The software can therefore be configured for multiobjective design exploration/search and optimization or to maximize/minimize any one of the eleven output variables.

The second domain concerns the preliminary design of cooling hole geometries of gas turbine blades in collaboration with Rolls Royce plc. The requirement here relates to rapid exploration of initial discrete geometries and dependent continuous variable sets in order to identify best design direction in terms of pressure ratios, number of passes,

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

film cooling requirement, etc. Although this could be treated as a routine design task by constraining search within known bounds based upon previous experience and knowledge, there is a strong requirement for a strategy that supports search outside of the initial brief in the expectation that innovative solutions can be found that, with appropriate off-line processing, will result in systems that support the maintenance of a competitive edge. A turbine blade cooling preliminary design model based upon empiric formulae is utilized to minimize coolant mass flow rate in a series of cooling hole geometries of a turbine blade. Discrete variables relate to three cooling hole geometries (plane, ribbed, and pedestal) and control the operating ranges of two of the eleven variables (heat transfer coefficient factor and coefficient of discharge) the remaining variables are common to all three geometry configurations. In this example, the model is used to minimize radial coolant mass flow rate whilst maintaining three other outputs within acceptable performance bounds.

In both design domains, the utilization of design models that are relatively coarse representations of the systems under design demands that a high degree of engineer involvement is required to assess output. The major utility of such models is that they can provide sufficient information to indicate optimal design direction and contribute significantly to the engineering knowledge base relating to the problem area. The purpose of the research described here is to extend their utility through their integration with interactive evolutionary exploration and search frameworks which allow rapid assessment both within and outside initial predefined bounds.

### 3.3. Single objective/continuous design space

In the following examples, vmCOGA is applied to both the Rolls Royce cooling hole problem and the BAe airframe problem. In both cases, vmCOGA is used in an investigative manner in order to build knowledge relating to the general nature of the predefined design space before better defining the high-performance regions. Initially, a low Rf filter setting is introduced which becomes more discriminatory in subsequent runs. The relatively simple representation of the systems under design results in short run times for the design models. This allows 250 generations of vmCOGA to be executed in approximately three minutes using a SUN Enterprise 4000 server with 167 MHz Ultrasparc processors. Thus, rapid investigation and designer interaction in terms of varying filter settings is supported.

Figure 4 illustrates this investigative process *via* two-dimensional hyperplanes of the twelve-dimensional Rolls Royce cooling hole model. The experimental graphical user interface allows the engineer to select a combination of any two variables in order to view the vmCOGA generated results across a range of two-dimensional hyperplanes of the overall design space. Each point in the figures indicates a design solution present in the final clustering set. Color coding indicates relative solution fitness. Clearly defined high-performance regions will emerge in some hyperplanes as in

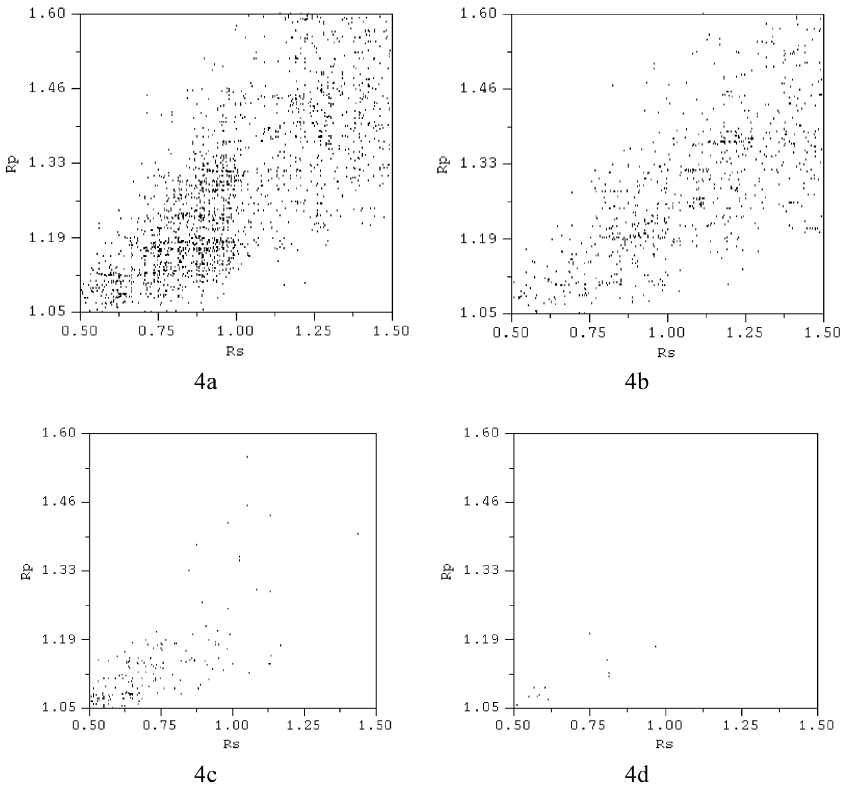



**Fig. 4.** Application of vmCOGA to cooling hole geometry problem.

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

the one shown (Perimeter Ratio (*Rs*)/Pressure Ratio (*Rp*); however, good solutions will be well distributed in others indicating that the problem is not particularly sensitive to at least one of the variables describing the hyperplane (see Section 4.2). In the example, 4a indicates that better solutions exist within a wide diagonal band which narrows as Rf settings tighten (4b & 4c). Finally, the space is decomposed into a small region in the lower left-hand corner containing several very high-performance solutions. The diagonal distribution of the solutions also indicates a linear relationship at least between the two variables of the hyperplane.

A similar sequence relating to the BAe model is shown in Figure 5. The results of each independent vmCOGA run are shown in two-dimensional hyperplanes of wing thickness-to-chord ratio against wing leading edge sweep angle. Again, when low filtering thresholds are used high levels of low fitness solutions pass into the final clustering set. This is illustrated by the ridge of solutions arcing from the top left to the bottom right of the two-dimensional hyperplane. As filtering is further increased this region decomposes into a narrow ridge of solutions. We gradually see the emergence of two high-performance regions in the top left and lower right quarters. At higher filtering thresholds the ridge further decomposes into two regions of high performance, A and B.

These examples clearly illustrate the effect of varying the filtering threshold. Low filtering provides the designer with maximum information relating to the general nature of the search space. Conversely, high filtering greatly reduces set cover and produces a limited number of near-optimal solutions. Table 1 gives the various vmCOGA parameter settings for the experimentation in the two problem areas. During preliminary runs utilizing low filter settings, the engineer may discover regions of medium performance in terms of the main quantitative objectives that could be considered high performance in terms of a range of alternative objectives (both qualitative and quantitative). Although these objectives may initially be considered to be of lesser importance, they may be of considerable significance if a certain payoff can be achieved by adopting an alternative design approach. Such regions can therefore be presented for design team discussion and further off-line investigation and processing resulting in a redefinition of the problem. Practising engineers are very aware of the existence of "interesting" solutions in addition to "high-performance solutions" in terms of major objectives. VmCOGA regional identification should support the discovery of interesting solutions and further investigation within existing design lead-time constraints.

### 3.4. Multilevel, mixed-parameter design space

The Rolls Royce cooling hole geometry model has three levels, each described by the characteristics of differing internal geometries (plane, ribbed, and pedestal). These characteristics are defined by differing values of discharge and

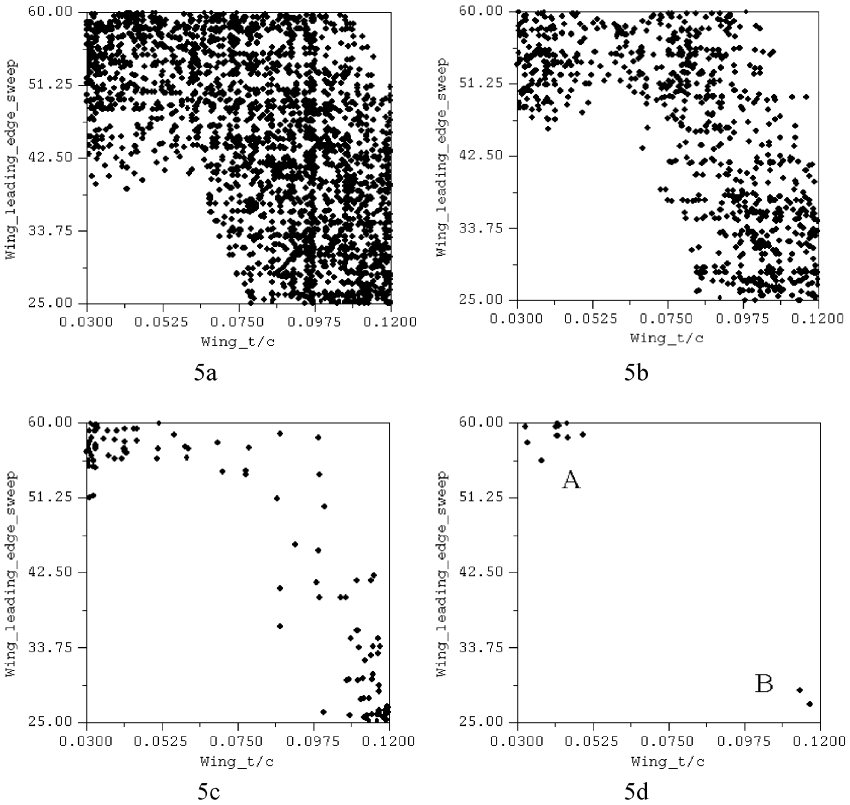



**Fig. 5.** Application of vmCOGA to preliminary airframe design.

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

**Table 1.** *Filtering thresholds used during single objective decomposition study*

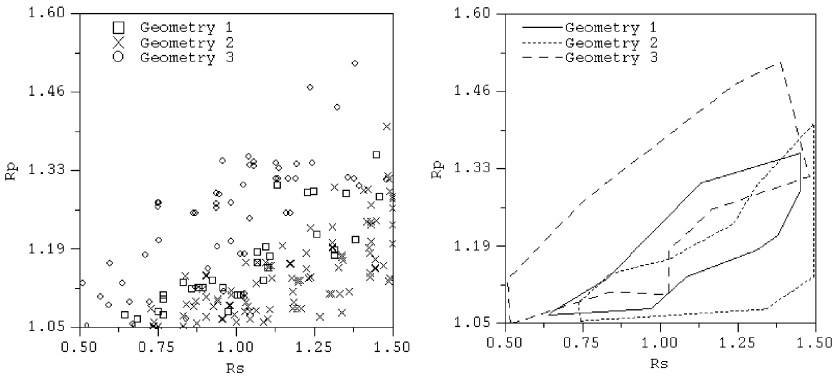
| | | | $Rf_i$ | | | |
|---|---|---|---|---|---|---|
| $st_n$ | $gen_i$ | $mp_i$ | 5a | 5b | 5c | 5d |
| 1 | 0 | 0.08 | n/a | n/a | n/a | n/a |
| 2 | 50 | 0.06 | 1.0 | 1.5 | 2.0 | 2.5 |
| 3 | 100 | 0.04 | 1.0 | 1.5 | 2.0 | 2.5 |
| 4 | 150 | 0.02 | 1.0 | 1.5 | 2.0 | 2.5 |
| 5 | 200 | 0.01 | 1.0 | 1.5 | 2.0 | 2.5 |
| 6 | 250 | n/a | 1.0 | 1.5 | 2.0 | 2.5 |

heat transfer coefficients. Independent fitness landscapes therefore exist for each of the internal geometries. Pedestal configurations will provide the best results in terms of minimum coolant flow rate as shown in Figure 4 where solutions from the plane and ribbed configurations, due to their relative low fitness, do not pass into the clustering set. However, there are several other quantitative and qualitative criteria that must be taken into account and any design decision must utilize previous experience when evaluating tradeoffs.

Representative results from each subregion are therefore extracted during search. A structured genetic algorithm, stGA (Dasgupta & MacGregor, 1991) with fitness scaling is used to encourage the generation of equal amounts of geometry one, two, and three solutions in the final clustering set. Figure 6a shows typical results on a two-dimensional hyperplane of radial passage perimeter ratio against inlet/outlet pressure ratio. Higher filtering thresholds have been utilized to reduce the size of the clusters to simplify graphical representation. The region boundaries relating to each geometry configuration are idealized using the outermost points of each cluster. Each configuration may therefore be assessed and compared, both quantitatively and qualitatively, by the designer. Of most significance, however, are those common regions where similar high performance can be achieved irrespective of internal geometry [i.e., $0.75 < Rs < 1.00$, $1.07 < Rp < 1.17$ (approximately)]. The engineer may previously have been unaware of such physical characteristics.

### 3.5. Multiobjective continuous search space

The vast majority of design problems involve many quantitative and qualitative criteria. Many techniques exist for combining objective vectors into a single scalar representation (Osyczka, 1984) or alternatively Pareto approaches (e.g., Horn & Nafpliotis 1993) can support the identification of a nondominated front containing solutions that best satisfy a range of objectives/criteria. Available techniques generally assume that all criteria are quantifiable, well defined (both mathematically and in terms of their relative importance), and that their importance does not alter as the problem knowledge base expands. During conceptual design, this is not the case and a high degree of flexibility is desirable when dealing with multiple objectives. The following approach presents the engineer with design information to support experience, knowledge, and intuition and will lead to the identification of an optimal design direction that best satisfies overall design requirements while incurring least possible risk. Risk in this case relates to the probability of the necessary introduction of major design change at a later stage. VmCOGAs can rapidly decompose complex design space in terms of high-performance solutions that satisfy individual objectives. Figures 7a–7c show the results of three independent vmCOGA runs using the miniCAPS model. In each run, a high-performance region is identified for an individual objective, that is, ferry range, subsonic-specific excess power (SEP), and subsonic-attained turn rate (ATR).




a) Results of vmCOGA run on multi-level turbine blade cooling model

b) Idealised regional boundaries

Geometry 1= Pedestal; Geometry 2 =Ribbed; Geometry 3 = Plane

**Fig. 6.** Application of vmCOGA to blade cooling model with fitness scaling relating to internal geometries and idealized definitions of high-performance regions.

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

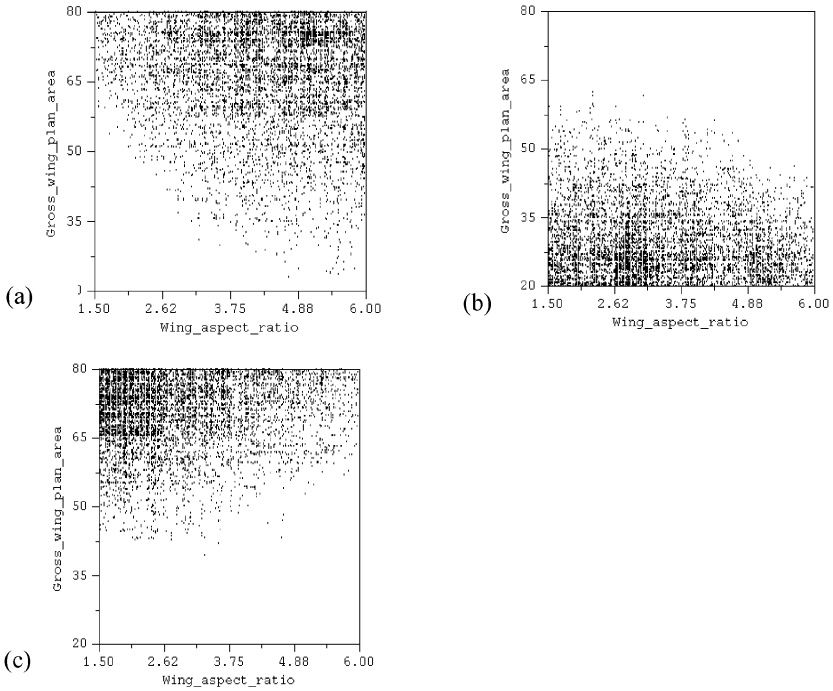
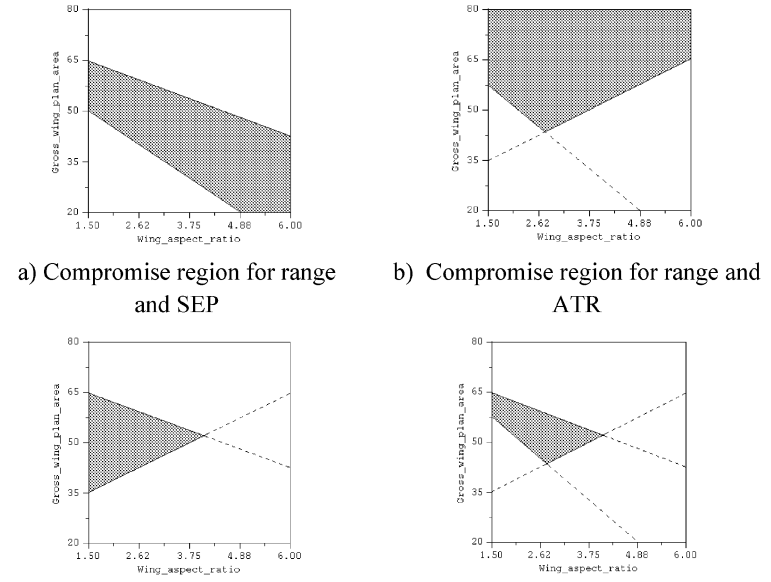



**Fig. 7.** vmCOGA applied to individual objectives using miniCAPS: (a) Maximizing range; (b) maximizing subsonic, specific excess power SEP; and (c) maximizing subsonic attained turn rate ATR.

It can be seen that the objectives are in conflict as the high fitness regions for each objective relate to differing regions in the wing aspect ratio, gross wing plan area hyperplane. The regions can be defined from data generated from three independent runs each addressing a different objective. It may then be assumed that any solutions contained within these regions will be similarly high fitness individuals in all objectives if they are equally weighted. Figures 8a–8c illustrate the construction of the compromise regions for each possible combination of the three objectives. In each figure, it can be seen that the compromise regions cover significantly differing regions of the design space for each objective combination. However, in every example the common region clearly indicates to the designer where future search may be concentrated to determine an optimal multiobjective design configuration.




a) Compromise region for range and SEP

b) Compromise region for range and ATR

c) Compromise region for SEP and ATR

d) Compromise region for range, SEP and ATR

**Fig. 8.** Identification of feasible high-performance regions relating to various objective combinations.

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

## 4. DISCUSSION

### 4.1. The COGA concept

The powerful design data processing capabilities of vmCOGA and the manner in which complex design space can be rapidly decomposed into succinct regions of high-performance solutions that satisfy several objectives has been illustrated. It is now intended to discuss the manner in which this interactive strategy can be utilized in order to support the designer during conceptual design where the engineer is attempting to explore across a broad set of design options; firm-up initial concepts and identify initial innovative design directions. The approach represents an information gathering process that can be utilized in an interactive manner to support the building of design team knowledge relating to the system under design. It is best integrated with conceptual design models that provide a degree of definition commensurate with the confidence in available data and the uncertainties relating to overall requirement. Such models should incur little computational expense. The processing capabilities of COGAs are not restricted to the manipulation of quantitative, mathematical models but can be equally applied to qualitative, rule-based representations, fuzzy logic (Zadeh, 1965; Roy et al., 1996) and neural network models. The concept is therefore well suited to domains where a high degree of uncertainty is prevalent.

The experimental graphical user interface allows the engineer to display the vmCOGA results as any two-dimensional combination of the variable parameters currently in use (several alternative two and three dimensional graphical representations are also available). Variables can be chosen for inclusion from a library specific to the current problem and variable bounds and constraint penalties can be altered. All variable parameters relating to vmCOGA (e.g., population size, generation number, filter settings, etc) can be adjusted.

The rapid data processing capabilities of COGAs support meaningful interaction with the human user in terms of an iterative procedure. Information gained from successive runs provides a basis for the variation of variable range and constraint/objective weightings and the addition/removal of variables, constraints, and objectives as their relative importance becomes apparent. The designer can therefore move from an initial design space defined on the basis of knowledge available at that time to other spaces that better satisfy emerging design requirement. In addition, it is suggested that the identification of disjoint design regions each containing high-performance solutions that satisfy requirements to a similar extent but in an entirely different manner in terms of variable values can, upon further off-line analysis, provide insight into underlying relationships. Recognition of such design commonalities may initially be based upon intuition (itself supported by experiential knowledge) which stimulates further appropriate designer/machine interaction resulting in significant changes to the structure of the problem.

The definition of common regions relating to multicriteria offers significant utility. It is probable that, initially, a feasible region containing solutions which satisfy all criteria will not be identified and discussion concerning relative importance of the various criteria and subsequent variation of criteria weightings or their removal will be required. Such designer/machine interaction may provide insight which either leads to the identification of a mutually inclusive region or the development and implementation of a revised structure. This is simply illustrated using the BAe model in Figures 9a–9e. With filter threshold settings of 1.0 for all objectives, a common region of high-performance solutions which satisfy Ferry Range and Turn Rate can be identified but solutions relating to Specific Excess Power (SEP) are not part of that region. However, by relaxing the filter threshold relating to SEP, lower performance solutions are allowed through to the final clustering set. The SEP region gradually expands until a feasible region for all three objectives is identified.

This relaxing of the filter threshold is equivalent to a reduction in importance of the SEP objective through an acceptance of lower fitness solutions whilst maintaining the higher relative fitness of Range and Turn Rate. The size and shape of the feasible region can be tailored to some extent through differing variation of the filter threshold of each of the objectives. Alternatively, equally low settings for all objectives can result in the mutually inclusive region of Figure 8. By varying filter settings for each objective, the engineer can explore the objective space relative to the variable space in terms of the two-dimensional hyperplanes. The flexibility of the graphical user interface allows objectives to be included or disregarded whilst also allowing variable ranges to be altered in order to support investigation of specific regions and objective/variable interaction. A facility therefore exists for concurrent search of both variable and objective space although aspects relating to cognitive overload suggest that some further machine-based support for such activity will be necessary.

One aspect of variable/objective interaction is shown in Figure 10. The left-hand column shows high-performance regions relating to (1) Turn Rate; (2) Excess Power, and (3) Ferry Range plotted in the gross wing plan area/wing aspect ratio hyperplane. These graphs plainly indicate the settings for upper and lower bounds of the two variables for further search effort. The right-hand column, however, shows the corresponding distribution of high-performance solutions in the climb Mach number/cruise height hyperplane. A uniform distribution of such solutions across this hyperplane is evident in (1) Turn rate and (2) Excess Power objectives and can be considered relatively uniform in the case of (3) Ferry range. This immediately provides an indication of the sensitivity of the objective functions to variation of the parameter values in each hyperplane. Although high-performance regions of gross wing plan area and wing aspect ratio values are significantly constrained, both climb Mach number and cruise height can take any value within

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

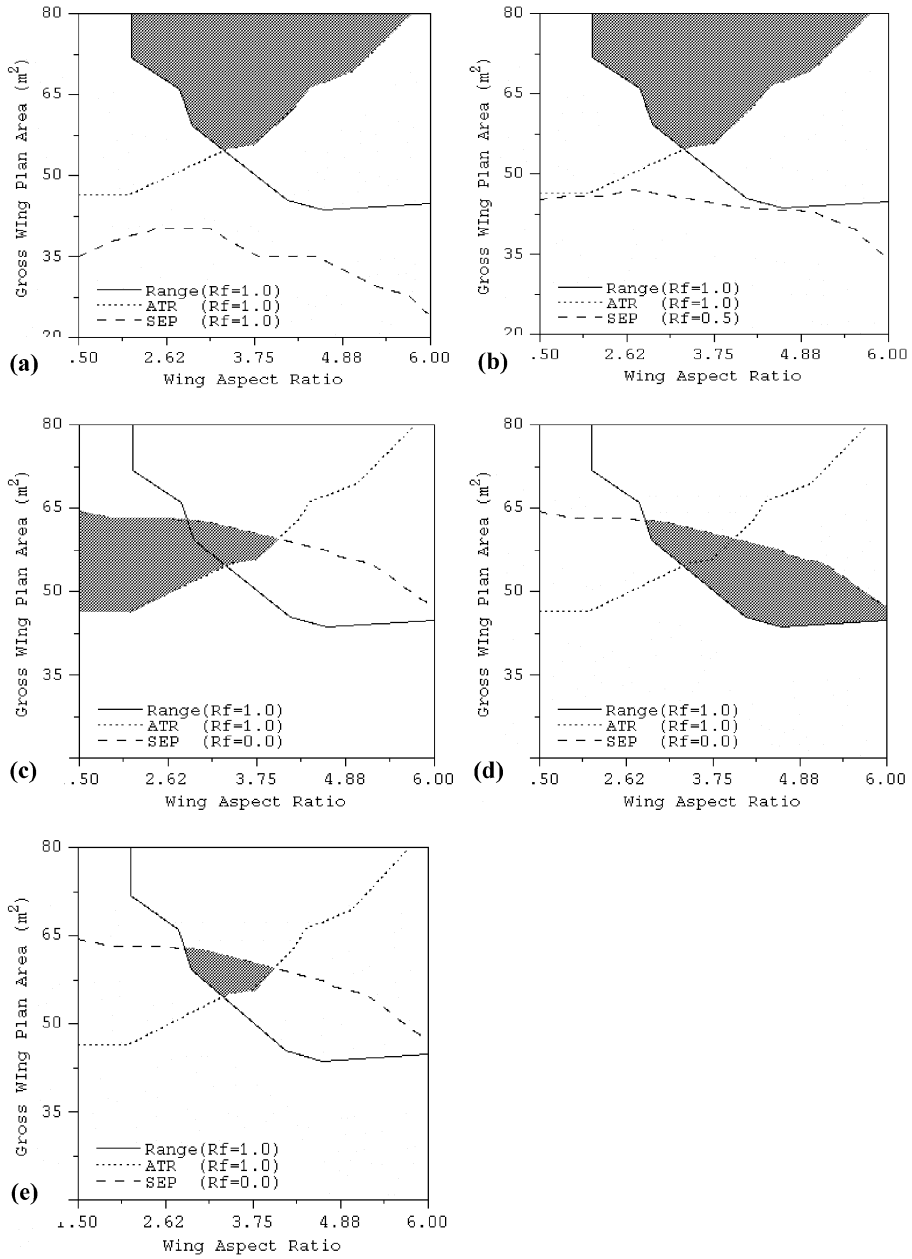



**Fig. 9.** Identification of feasible high-performance regions relating to various objective combinations through filter threshold relaxation. (a) A common region containing high-performance solutions for Ferry Range and Turn Rate has been identified but Specific Excess Power objectives cannot be satisfied. (b) Relaxing the filter threshold for SEP allows lower fitness SEP solutions through and boundary moves towards feasible region. (c), (d), and (e) Further relaxation results in the identification of a feasible region for all objectives.

existing upper and lower bounds. The engineer can thus fix values that are of seemingly best benefit thereby effectively removing these variables from future search. This visual measure can rapidly provide an overall indication of the degree of interaction between those variables considered most significant to the engineer. Variables and objectives can be made temporarily redundant whilst others can be introduced during a largely explorative process. However, increased dimensionality and rapid associated increase in number of available hyperplanes will require the inclusion of machine-based data analysis to support such engineer interaction (see Sections 4.2 and 4.3).

Appropriate use of the graphical user interface in both variable and objective space can thus provide the engineering designer with much relevant information for discussion and analysis. Such discussion may capture intuitive aspects and problem insight based upon previous experience during problem reformulation. Initial demonstration of the tech-

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

niques to a range of industrial collaborators indicates that the speculation here upon the system's utility is well founded. Experienced engineers have rapidly become engrossed with the possibilities of the approach and intrigued by some of the results when given access to hands-on experimentation. Initial reactions show that results from the system certainly promote debate and off-line related problem exploration. Although not scientifically founded, this reaction indicates that one initial objective to develop an interactive design tool that promotes discussion and innovation through related design team activity will likely be satisfied to some extent within the short to medium term.

### 4.2. Further research

Research related to a minimization of required calls to the evaluation function coupled with distribution across several processors will further reduce the run times of COGA with obvious benefits in terms of iterative designer/machine interaction. Such run time issues are under investigation in addition to scaleability aspects relating to the performance of the technique in higher dimensional design domains. An important issue here is the presentation of results as the numbers of available hyperplanes greatly increases with dimension. Significant research resource is concentrating upon this aspect. Intelligent agent technologies are under investigation to ascertain their potential for filtering and presentation of higher dimensional information.

The nature of the distribution of solutions across various selected hyperplanes can provide significant information relating both to the relationship between the variables involved (i.e., linear/nonlinear; illustrated by the differences in distribution of solutions in Figures 5 and 6) and in the sensitivity of the problem to each variable as shown in Figure 10. This area requires further research, the objective being the on-line identification of problem characteristics and analysis of solution distribution leading to machine-based identification of variable redundancy and a reduction in problem dimensionality. Both solution sensitivity and variable sensitivity have been addressed in previous work as has degree of constraint violation and qualitative evaluation of GA-generated quantitative solutions (Parmee & Denham, 1994; Roy et al., 1996). Further on-line strategies for such extraction, analysis, and presentation are currently under investigation.

### 4.3. Related research

The COGA strategies represent a significant component of research relating to the development of a prototype interactive evolutionary design station (IEDS). Recent related research indicates that cooperative frameworks involving a number of search strategies/optimization techniques operating concurrently within single or multilevel environments can offer significant utility (Parmee, 1997, 1999*a*) within the complex, rapidly changing environment of conceptual design. The additional integration of complementary computational intelligence (CI) techniques can result in search and processing capabilities that can significantly support the engineer. Fuzzy technologies (Zadeh, 1965), for example, when integrated with evolutionary search, may best handle the uncertainties inherent in high-level design (Roy et al., 1996; Brehm et al., 1997). Emerging intelligent agent technologies (Wooldridge & Jennings, 1995) also offer considerable potential for co-evolutionary state recognition and subsequent reactive or proactive involvement in addition to providing appropriate communication and constraint satisfaction protocols. However, in order to establish meaningful, coherent designer/machine-based systems, significant research is also required relating to the human-centered aspects of the iterative information feedback loop which forms the essential component of an overall evolutionary exploratory framework.

The envisaged structure of the IEDS is shown in Figure 11. At its core are a number of co-evolutionary processes concerning closely related but differing aspects of the design problem at hand. Scenarios A, B, and C may, for instance, relate to mechanical, aerodynamic, and thermal aspects of some element of preliminary gas turbine design or various operational scenarios relating to preliminary airframe design. In order to maintain their concurrent evolution, a communication protocol relating to conflicting constraint and objective satisfaction must be maintained. Investigation of intelligent agent technologies is assessing their potential for providing such communication control in terms of state recognition relating to degree of convergence and constraint/objective satisfaction and subsequent reactive activity relating to reallocation of search resource, softening/hardening of conflicting constraints, and variable weighting of objectives. A filtering aspect relating to the presentation of relevant information concerning the implementation of such actions and their effect to the design team must be considered. Interaction with the process takes place either directly or through the revision of rule-based preference ratings. Information can also be archived in the on-line database and extracted when required. COGAs reside within the information gathering processes that constantly extract information for presentation to the design team.

The performance of each component operating in a standalone manner has been investigated (Cvetkovic & Parmee, 1999; Parmee & Watson, 1999; Bonham & Parmee, 1999*a*, 1999*b*; Parmee, 1999*c*). Current work is addressing their integration within the IEDS to enhance and extend design team capability whilst capturing design knowledge through significant interaction.

The IEDS is firmly placed within conceptual design manipulating relatively simple design models. This moves away from optimization through the standard application of evolutionary search over a preset number of generations or until convergence has been achieved. The IEDS would be a continuous, dynamic explorative process commencing from an initial design space defined from current available

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

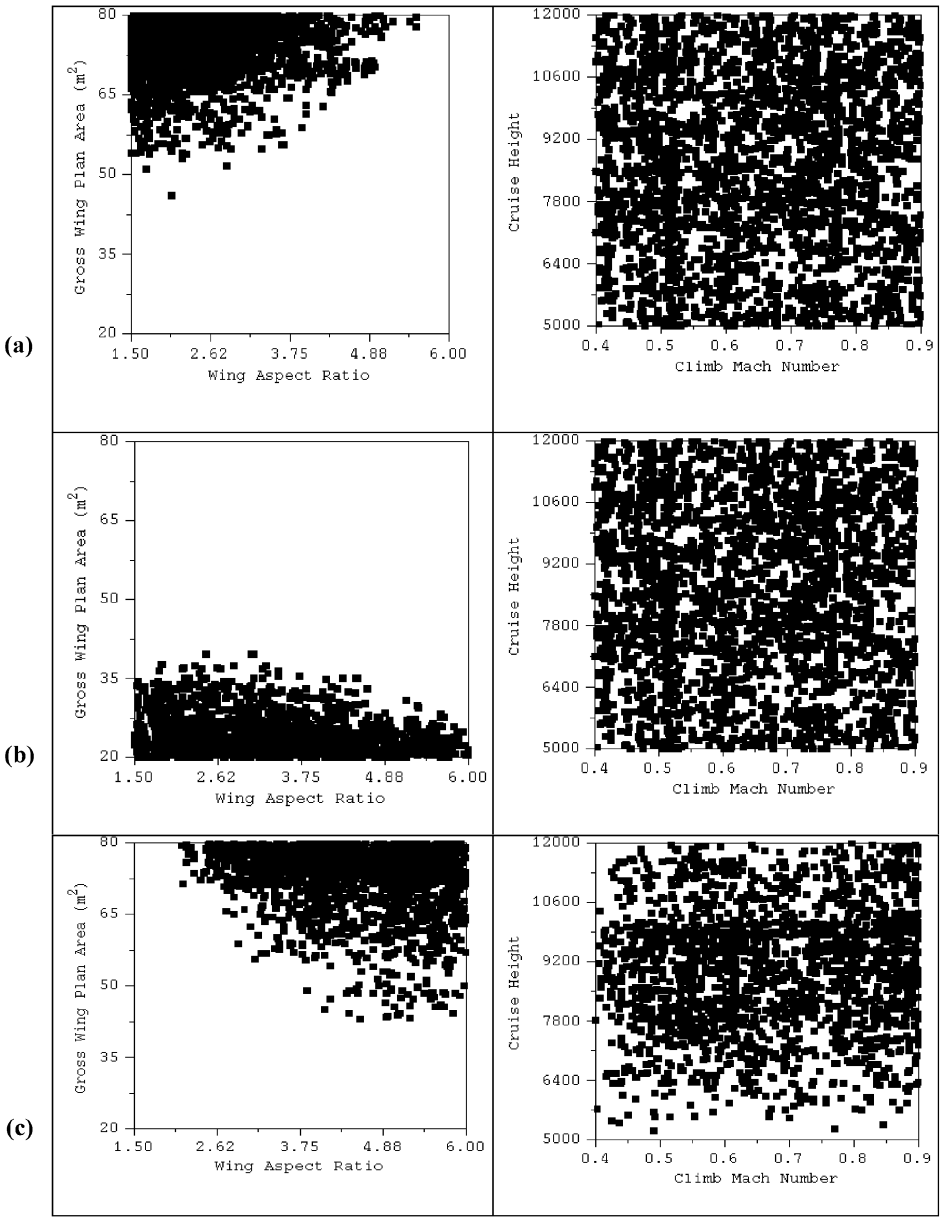



**Fig. 10.** Objective sensitivity reselected variable parameters.

knowledge. Subsequent iteration involving experiential knowledge and the search capabilities of the evolutionary technologies supported by machine-based agent processing may result in a reformulation of the design problem. Such a concept could best utilize the capabilities of future computing technology during the complex human/machine-based activities of conceptual design by providing the ability of search across a vast number of design alternatives within acceptable lead time limitations.

## 5. CONCLUDING REMARKS

The vmCOGA strategy has been described and the technique's data processing capabilities illustrated through application to two-dimensional test functions and within complex real-world design domains. Results indicate how exploration is supported by filter threshold variation, search across differing problem structures, and investigation of objective interactions. COGA experimentation has led to discussion concerning further exploration through variation of parameters, constraints, and objectives and speculation concerning the integration of COGA techniques with design team practice; the expansion of design team knowledge and subsequent problem redefinition.

Further minimization of evaluation calls, distribution of the underlying GA process, and increasing processor speed should lead to the availability of results in seconds rather than minutes. The possibility of virtual real-time inter-

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

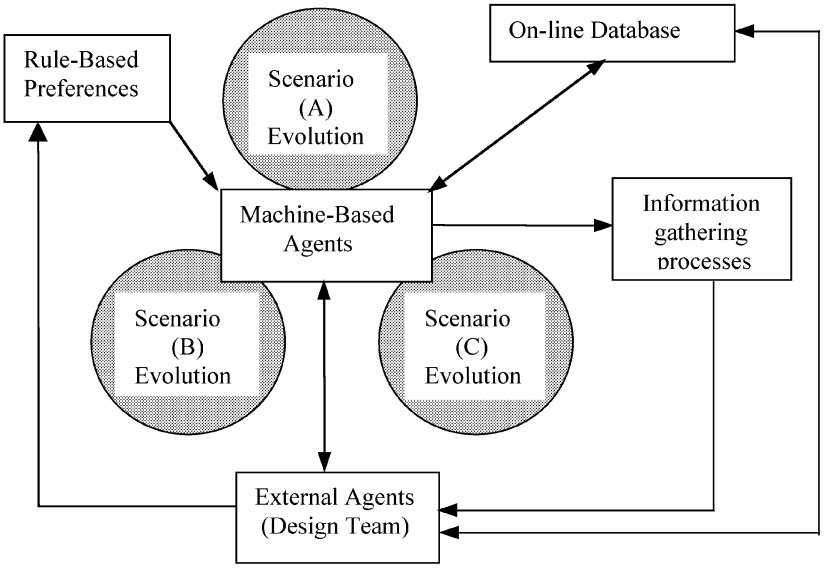



**Fig. 11.** Interactive evolutionary design station structure.

action in the medium term seems likely. The realization of low-cost, extensive conceptual design exploration leading to significant discovery in terms of knowledge, new concepts, and radical design is possible.

The establishment of the IEDS is an ambitious objective. However, in order to best utilize future computing capabilities such research and the introduction of experimental prototypes are seen as essential. An under-utilization of current machine capability during conceptual design is apparent. The complexity of group working and decision making, the utilization of experiential knowledge and intuitive judgement, and related human/machine interaction results in limited software support. The proposed integration of evolutionary search and exploration technologies and other computational intelligence techniques offers a potential environment that, while best utilizing computational processing capability, also allows extensive designer interaction and the capture of knowledge generated from human-based reasoning and activity. A much improved take-up of advanced computing within complex conceptual design environments is the overall objective.

## ACKNOWLEDGMENTS

The main body of this work was presented at the 4th International Conference on Computational Models of Creative Design in December, 1998 (Parmee & Bonham, 1998). An abridged version of the paper has been presented at the IEEE Congress on Evolutionary Computation (Parmee & Bonham, 1999). The introduction of Section 2 has been previously published in the various referenced papers where details relating to initial development can be found. Full coverage of the COGA techniques including more recent developments will be available in Parmee, 1999*b*. The research has been supported by the UK Engineering and Physical Science Research Council, Rolls Royce, and British Aerospace. We wish to thank all of these organizations for their support

## REFERENCES

Bonham, C. & Parmee, I.C., (1999*a*). Improving the performance of cluster-oriented genetic algorithms (COGAs). *Proc. IEEE Congress on Evolutionary Computing*, pp. 1491–1497. Washington, D.C.

Bonham, C. & Parmee, I.C., (1999*b*). An investigation of exploration and exploitation within cluster-oriented genetic algorithms. *Proc. Genetic and Evolutionary Computation Conference*, pp. 1491–1497. Orlando, Florida.

Brehm, R., Kreise, T., & Sebastian, H-J. (1997). Fuzzy sets in engineering design. *Proc. IDEA '97—Intelligent Design in Engineering Applications Symposium, 5th European Congress on Intelligent Techniques and Soft Computing*, pp. 1–6. Elite Foundation, Aachen, Germany.

Cvetkovic, D. & Parmee, I.C. (1999). Use of preferences for GA-based multi-objective optimisation. In (Banzhaf, W. et al., Eds.) *GECCO—99: Proc. Genetic and Evolutionary Computation Conference*, pp. 1504–1509. Orlando, Florida.

Dasgupta, D. & MacGregor. (1991). *A structured genetic algorithm*. Research Report IKBS-2-91. University of Strathclyde, UK.

Gero, J.S., Louis, S.J., & Kundu, S. (1994). Evolutionary learning of novel grammars for design improvement. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 8*, 83–94.

Goldberg, D.E. (1989). *Genetic Algorithms in Search, Optimisation & Machine Learning*. Addison-Wesley Publishing Co., Reading, Massachusetts.

Horn, J. & Nafpliotis, N. (1993). *Multiobjective optimisation using the niched pareto genetic algorithm*. IlliGAL Report No. 93005. Illinois Genetic Algorithm Library.

Osyczka, A. (1984). *Multicriterion Optimisation in Engineering*. Ellis Horwood Series in Engineering Science, Ellis Horwood.

Parmee, I.C. & Denham, M.J. (1994). The integration of adaptive search techniques with current design practice. In *Proceedings of Adaptive Computing in Engineering Design and Control*, (Parmee, I.C., Ed.), pp. 1–13. University of Plymouth, UK.

Parmee, I.C. (1996*a*). The maintenance of search diversity for effective design space decomposition using cluster oriented genetic algorithms (COGAs) and multi-agent strategies (GAANT). In *Proceedings of Adaptive Computing in Engineering Design and Control*, (Parmee, I.C., Ed.), pp. 128–138. University of Plymouth, UK.

Parmee, I.C. (1996*b*). Cluster oriented genetic algorithms (COGAs) for the identification of high-performance regions of design spaces. *First Int. Conf. on Evolutionary Computation and its Applications, EvCA 96*, pp. 66–75. Presidium of the Russian Academy of Sciences, Moscow.

Parmee, I.C. (1997). Strategies for the integration of evolutionary/adaptive search with the engineering design process. In *Evolutionary Algorithms in Engineering Applications*, (Dasgupta, D. & Michelewicz, Z., Eds.), pp. 453–478. Springer-Verlag.

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press

Parmee, I.C. & Beck, M.A. (1997). An evolutionary agent assisted strategy for conceptual design space decomposition. In *Evolutionary Computing: Selected Papers from the 1997 AISB International Workshop*, (Corne, D. & Shapiro, J.L., Eds.), pp. 275–286. Springer Lecture Notes in Computer Science, No 1305, Springer-Verlag.
Parmee, I.C. (1998). Exploring the design potential of evolutionary/adaptive search and other computational intelligence technologies. In *Adaptive Computing in Design and Manufacture*, (Parmee, I.C., Ed.), pp. 27–44. Springer-Verlag.
Parmee, I.C. & Bonham, C.R. (1998). Supporting innovative and creative design using interactive designer/evolutionary computing strategies. *Proc. Computational Models of Creative Design Conference*, University of Sydney, Heron Island, Australia.
Parmee, I.C. (1999*a*). Exploring the design potential of evolutionary search, exploration and optimisation. In *Evolutionary Design by Computers*, (Bentley, P., Ed.). Academic Press, London.
Parmee, I.C. (1999*b*), *Evolutionary and Adaptive Computing in Engineering Design*. Springer-Verlag, (in press).
Parmee, I.C. (1999*c*). Designing the evolutionary design station. *Proc. Int. Conf. Engineering Design*, Munich, Germany.
Parmee, I.C. & Watson A.H. (1999). Preliminary airframe design using co-evolutionary multiobjective genetic algorithms. In *GECCO-99: Proc. Genetic and Evolutionary Computation Conference* (Banzhaf, W., Daida, J., Eiben, A., Garzon, M., Honavar, V., Jakiela, M., & Smith, R., Eds.), pp. 1657–1665. Orlando, Florida.
Parmee, I.C. & Bonham, C. (1999). Cluster-oriented genetic algorithms to support interactive designer/evolutionary computing systems. *Proc. IEEE Congress on Evolutionary Computing*, pp. 546–555. Washington D. C.
Roy, R., Parmee, I.C., & Purchase, G. (1996). Integrating the genetic algorithm with the preliminary design of gas turbine cooling systems. In *Proc. 2nd Int. Conf. on Adaptive Computing in Engineering Design and Control*, (Parmee, I.C., Ed.), pp. 228–235. PEDC, University of Plymouth, UK.
Schnier, T. & Gero, J. (1998). From Mondrian to Frank Lloyd Wright: Transforming evolving representations. In *Adaptive Computing in Design and Manufacture*, (Parmee, I.C., Ed.), pp. 207–221. Springer-Verlag, London.
Wooldridge, M. & Jennings, N.R. (1995). Intelligent Agents: Theory and Practice. *Knowledge Engineering Review 10 (2)*.
Zadeh, L.A. (1965). Fuzzy sets. *Journal of Information and Control 8*, 29–44.

---

**I.C. Parmee** has worked in evolutionary and adaptive computation since 1988 developing generic evolutionary search strategies for conceptual, embodiment and detailed design processes in a wide range of engineering domains. He is the Director of the Plymouth Engineering Design Centre (PEDC), and Reader in Evolutionary Design at the University of Plymouth co-ordinating a team of researchers working in the field of evolutionary and adaptive computing in engineering design. He chairs the biennial "Adaptive Computing in Design and Manufacture" conference that has a wide international following. He also co-ordinates the UK Engineering and Physical Science Research Council's Engineering Network in Adaptive Computing in Design and Manufacture (ACDM-net). European involvement includes the co-ordination of EvoDES, which is an EVONET (EC Network of Excellence in Evolutionary Computation), working group in evolutionary design. Details of all of these activities can be found at: http://www.tech.plym.ac.uk/soc/research/edc

https://doi.org/10.1017/S0890060400141010 Published online by Cambridge University Press