F1.2 Management applications and other classical optimization problems

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Abstract

In this section an evaluation of the current situation regarding evolutionary algorithms (EAs) in management applications and classical optimization problems is attempted. References are divided into three categories: practical applications in management, application-oriented research in management, and standard optimization problems with relevance beyond the domain of management. Some general observations on the competitiveness of EAs, as compared to other optimization techniques, are also given. Few systematical and large-scale comparisons have appeared in the literature so far, and it is fair to state that a thorough evaluation of the potential of EAs in most of the classical optimization problems is still ahead of us. This is partly due to the lack of suitable benchmark problems, representative for distinct and neatly specified problem classes. Besides, theoretical results also shed a rather critical light on the objectives and current practice of empirical comparisons.

F1.2.1 Introduction

In recent years, new heuristic techniques, some of them inspired by nature, have emerged which have proven successful in solving very diverse hard optimization problems. Evolutionary algorithms (EAs), *tabu search* (TS), and *simulated annealing* (SA) are probably the best known classes of these modern heuristics. They share common characteristics. For instance, they tolerate deteriorations of the attained solution quality during the search process to overcome local suboptima in complex search spaces. D3.5

In this section†, EAs are viewed as stochastic heuristics, applicable to a large variety of complex optimization problems. They are based on the mechanisms of natural evolution, imitating the phenomena of heredity, variation, and selection on an abstract level. The mainstream types of EA are:

- *genetic algorithms* (GAs) B1.2
- *genetic programming* (GP) B1.5.1
- *evolution strategies* (ESs) B1.3
- *evolutionary programming* (EP). B1.4

Research in EAs is growing rapidly. This has been most visibly documented in a number of conference proceedings (Grefenstette 1985, 1987, Schaffer 1989, Belew and Booker 1991, Schwefel and Männer 1991, Männer and Manderick 1992, Fogel and Atmar 1992, 1993, Sebald and Fogel 1994, Davidor *et al* 1994, Pearson *et al* 1995, Eshelman 1995, McDonnell *et al* 1995). The field becomes increasingly diversified and complex.

In an attempt to structure one important area of applied EA research, this paper gives an overview of EA in management applications, also covering other classical optimization problems with relevance beyond the domain of management. More than 850 references to current as well as finished research projects and practical applications are classified in Appendix B. (The references in this text are collected in a separate reference list, located before the appendices.) Although much effort has been devoted to

† This section is an updated and extended version of Nissen (1993, 1995).

collecting and evaluating as many references as possible, the list cannot be complete. Furthermore, it must be assumed that many applications remain unpublished for reasons of confidentiality. Hence, the results reported in section F1.2.2 might be unintentionally biased. However, it is hoped that others will find the classification of applications and extensive reference list helpful in their own research. Moreover, some general observations on the competiveness of evolutionary approaches as compared to other paradigms are included in section F1.2.3.

F1.2.2 An overview of evolutionary algorithm applications in management science and other classical optimization problems

F1.2.2.1 Some technical remarks

This overview is mainly based on an evaluation of the literature and information posted to the relevant e-mail discussion lists *Genetic Algorithms Digest* (ga-list-request@aic.nrl.navy.mil), *Evolutionary Programming Digest* (ep-list-request@magenta.me.fau.edu), *Genetic Programming List* (genetic-programming-request@cs.stanford.edu), the EMSS list (dduane@gmu.edu) on evolutionary models in the social sciences, and two other specialized lists on timetabling (ttp-request@cs.nott.ac.uk) and scheduling (gasched-owner@acse.sheffield.ac.uk) with EAs. Additional information was gathered by private communication with fellow researchers, consultants, software developers, and users of EAs in business.

Sometimes it was rather difficult to decide, on the basis of the literature reviewed, whether papers actually discussed a practical application in business (section F1.2.2.2) or 'just' application-oriented research (section F.1.2.2.3). When only test problems were discussed without reference to a practical project then no immediate practical background was assumed. This also applies to projects using historical real data. Application-oriented research in management, and other classical optimization problems (section F1.2.2.4) are two evaluations that refer to projects not linked to practical applications in business. The section on other classical optimization problems concerns management as well as different (e.g. technical) domains. A well-known example for such a general standard problem with applicability in different domains is the *traveling salesman problem* (TSP). G9.5

Multiple publications on the same project count as one application, but all evaluated references are given in the tables of Appendix A and are listed in the extensive bibliography of Appendix B. The year of earliest presentation of an application, as given in the tables, generally refers to the earliest source found, which might be personal communication preceding a publication. In some cases, authors (Koza, Michalewicz) have included all previously published material in easily accessible books or long papers. Here, only the overall references are cited in the reference list.

For the majority of cited references the original papers were available for investigation. In some cases, however, secondary literature had to be used, because it was impossible or too difficult to obtain the original sources. Some additional references may be found in the bibliographies compiled by Alander (1996a, b, c, d) and available through the Internet (ftp://ftp.uwasa.fi.directory.cs/report94-1).

In this section, and particularly in the tables, a unified view on the field of EAs is taken. Even though the GA community is by far the largest, it is probably true that any of the EA mainstream types could be applied to any of the fields discussed here. Generally, a good optimization technique will account for the properties and biases of the problem investigated. The most reasonable solution representation, search operators and selection scheme will, therefore, depend on the problem. In this context, the entire field of EAs may be thought of as some form of toolbox. Whether the result of EA design for a particular problem on the basis of such a toolbox is called a GA, GP, EP or an ES is not really important, and might even be hard to decide. However, in the following overview sections the frequency of certain EA mainstream types will be mentioned for reasons of completeness.

F1.2.2.2 Practical applications in management

An overview of practical management applications is given in table F1.2.1. To date the quantity and diversity of applications is still moderate if one compares with the huge variety of optimization problems faced in management. Besides, many systems refered to in table F1.2.1 must be considered prototypes. Although the information is hard to extract from the given data, the number of running systems actually applied routinely in daily practice is likely to be rather small.

Combinatorial optimization with a focus on scheduling is most frequent. The majority of applications appear in an industrial setting with emphasis on production (figure F1.2.1). This is not surprising, since

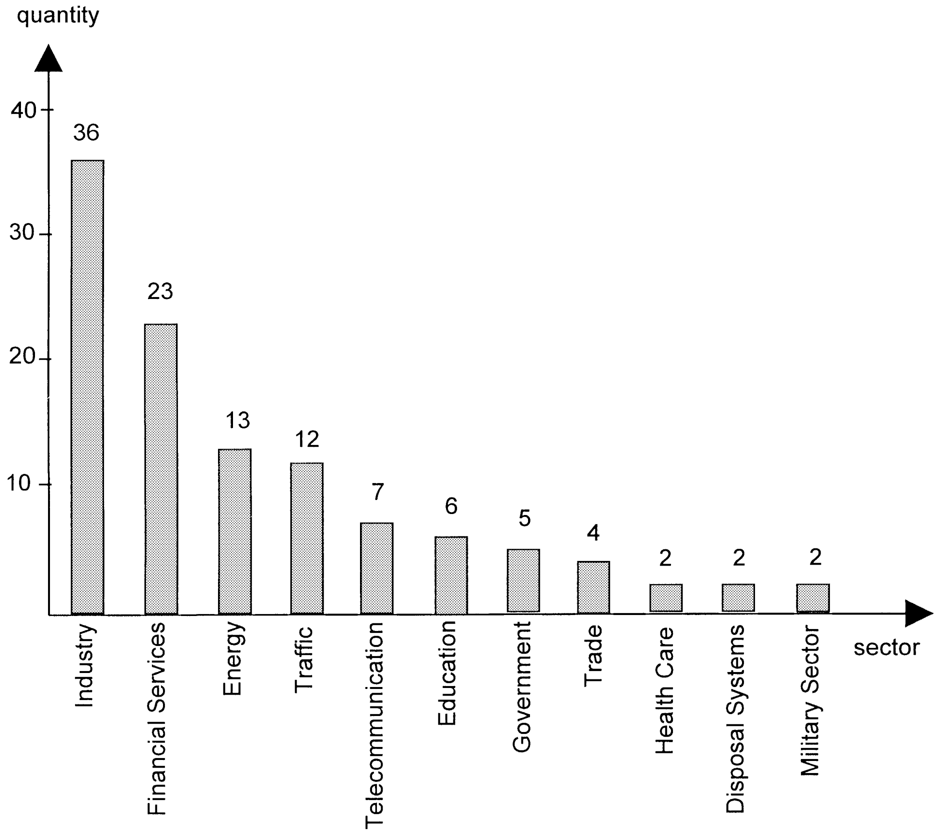

Figure F1.2.1. Practical applications ordered by economic sectors, as of July 1996.

production can be viewed as one large and complex optimization task that determines a company's competitive strength and success in business. Other business functions such as strategic planning, inventory, and marketing have not received much attention from the EA community so far, although some pioneering publications (see also table F1.2.2) have demonstrated the relevance of EAs to these fields.

The financial services sector is usually progressive in its electronic data processing applications, but publications in the scientific press are rather scarce. A focus on credit control and identification of good investment strategies is visible, though. The actual number of EA applications in this sector is likely to be *much* higher than the figures lead us to believe. This might also hold for management applications in the military sector. In these unpublished applications GAs are the most likely type of EA employed, since their research community is by far the largest.

The energy sector is another prevailing area of application. ESs are quite frequent here, because this class of EAs originated in the engineering field and has traditionally been strong in technical applications.

GAs are most frequently applied in practice. Interest in the other EA types is growing, however, so that a rise in the number of their respective applications can be expected in the near future. ESs and EP already cover a range of management-related applications. GP is a very recent technique that has attracted attention mainly from practitioners in the financial sector, while GP researchers are still working to reach the level of practical applicability in other domains.

Some hybrid systems integrating EAs with *artificial neural networks*, *fuzzy set theory*, and rule-based systems are documented. Since they are expensive to develop and may yield considerable strategic advantage over competitors, it can be assumed that much work in hybrid systems is kept secret and does not appear in the figures. This also holds for applications developed by commercial EA suppliers, sometimes with the aid of professional and semiprofessional EA tools. The quality of the data suffers from the fact that many authors are not allowed to publish their applications for reasons of confidentiality. D1, D2

If one considers the publication dates of practical EA applications (figure F1.2.2), a sharp rise in publications since the late 1980s is obvious. This movement can almost solely be attributed to an increased interest in GAs where the number of researchers has risen dramatically. To infer that GAs

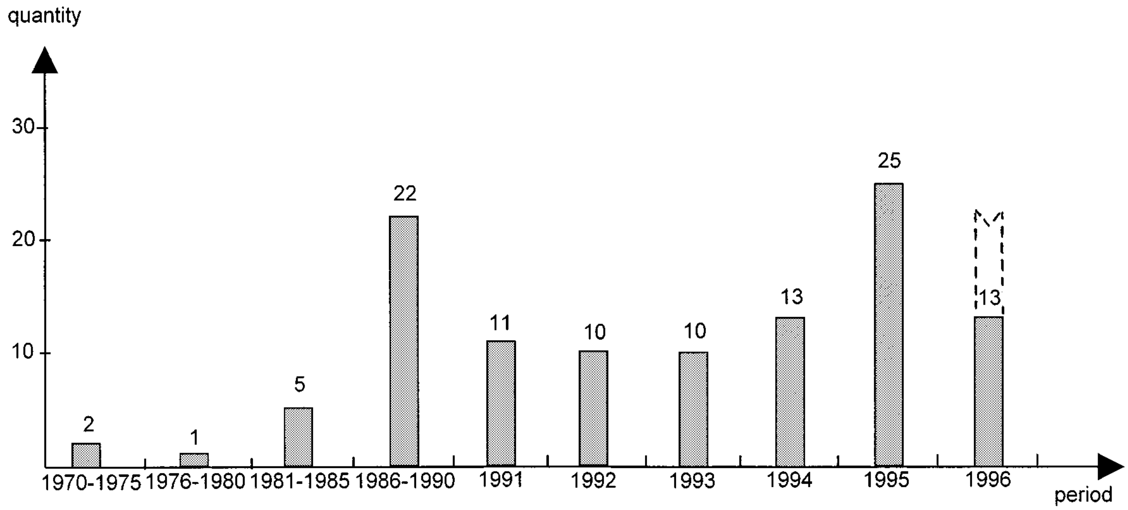

Figure F1.2.2. Practical applications ordered by earliest year of presentation as of July 1996.

are superior to other EA mainstream types can not be justified by these figures, though. It is rather the good 'infrastructure' of the GA community that fuels this trend: regular GA conferences since 1985, the availability of introductory textbooks, (semi-) professional GA tools, a well-organized and widely distributed newslist (*GA Digest*), and cumulative effects following successful pilot applications.

All in all, it seems fair to say that we have not seen the big breakthrough of EAs in management practice, yet. Interest in these new techniques, however, has risen considerably since 1990 and will lead to a further increase in practical applications in the near future.

F1.2.2.3 Application-oriented research in management science

This evaluation (table F1.2.2) focuses on research in management science that is not linked to any practical project in business. There is a strong focus on GAs, even more than in practical applications. The overall picture with respect to major fields of interest and EA types used is similar to that of the previous section. However, the quantity and diversity of projects is larger than in practical applications. Research interest in production planning and financial services is particularly high.

Notable is the strong bias of research for jobshop and flowshop scheduling. Production planning is an important problem in practice, of course. However, the standard test problems used by many authors frequently lack many of the practical constraints faced in production (see also section F1.2.3). Research on standard operations research problems such as jobshop scheduling sometimes seems to be some sort of tournament where the practical relevance of the approach comes second to minimal improvements of some published benchmark results on simplifying test problems.

F1.2.2.4 Other classical optimization problems

Table F1.2.3 lists EA applications on classical optimization problems with relevance to not only management science but other domains as well. Many of them refer to randomly generated data or benchmark problems given in the literature. The interested reader will find some applications from evolutionary economics under the heading *iterated games*.

Besides GAs (most frequent) and ESs, some applications of EP, GP and learning classifier systems are found in the area of game theory, as well as in some combinatorial problems such as the TSP. The TSP is a particularly well-studied problem that has led to the creation of a number of specialized recombination operators for GAs. The potential of GAs for the field of combinatorial optimization is generally considered to be high, but there has been some scientific dispute on this theme (see *GA Digest* **7** (1993), issue 6 and subsequent issues).

F1.2.3 Some general observations on the competitiveness of evolutionary algorithms

F1.2.3.1 Mixed results

Given the limited space available, it is impossible to discuss here in detail the implementations, advantages and disadvantages of EAs in particular optimization problems. However, some rather general observations will be presented that follow from the published literature, personal experience, and discussions of the author with developers and users of EAs.

Only a few systematic and large-scale empirical comparisons between EAs and other solution techniques appear in the literature. The most recent and quite extensive investigation was carried out by Baluja (1995). He compares seven iterative and evolution-based optimization techniques on 27 static optimization problems. The problem set includes jobshop scheduling, TSP, knapsack, binpacking, neural network weight optimization, and standard numerical function optimization tasks. Such problems are frequently investigated in the EA literature. Two GAs, three variants of multiple-restart stochastic iterated hillclimbing, and two versions of population-based incremental learning are compared in terms of speed and the best solution found in a given number of trials. The experiments indicate that algorithms simpler than standard GAs can perform competitively on both small and large problem instances.

Other empirical studies support these results. For instance, the investigations by Park and Carter (1995), Park (1995), Goffe *et al* (1994), Ingber and Rosen (1992), and Nissen (Section G9.10 of this handbook) all show no advantage or even disfavor EAs over SA and the related threshold accepting heuristic on classical optimization problems such as the Max-Clique, Max-Sat, and quadratic assignment problems. G9.10

In contrast, many examples can be found in the literature where evolutionary approaches compete successfully with the best solution techniques available so far. We only mention the works of Falkenauer on *binpacking* and grouping problems (Falkenauer and Delchambre 1992, Falkenauer 1994, 1995), Khuri *et al* on vertex cover and *multiple-knapsack* problems (Khuri *et al* 1994, Khuri and Bäck 1994), Lienig and Thulasiraman on routing tasks (Lienig and Thulasiraman 1994), Fleurent and Ferland on the *quadratic assignment problem* (Fleurent and Ferland 1994), and Parada Daza *et al* on the two-dimensional guillotine cutting problem (Parada Daza *et al* 1995). Moreover, the author knows of further practical applications of EAs in business where excellent results were produced in highly constrained complex search spaces. F1.7 G9.7 G9.10

These rather mixed results pose a problem for practitioners in search of the most promising optimization technique for a given hard problem. On the one hand, the current situation reflects the enormous difficulties associated with empirical crossparadigm comparisons. These difficulties concern benchmark problems and benchmark results. On the other hand, theoretical evidence suggests that the quest for a universally superior optimization technique is ill directed. The following sections take up these issues in some more depth.

F1.2.3.2 Benchmark problems

The first requirement for a systematic empirical comparison of different optimization methods is a representative set of instances for the investigated problem class. This in turn demands the neat specification and description of the relevant characteristics of this class. As Berens (1991) correctly points out, the success of an optimization method may change drastically when parameters of the given problem class are varied. Examples of such parameters are the problem size as well as structural aspects (such as symmetry and variance of entries in data matrices).

Moreover, real-world applications often involve multiple goals, noisy or time-varying objective functions, ill-structured data, and complex constraints that are usually not covered by standard test problems available today. Thus, if one does not want to be restricted to trivial toy problems many details can be necessary to correctly specify a problem class, and a sizeable number of problem instances might be required to cover the class representatively. As an example, Brandeau and Chiu (1989) have identified 33 characteristics to specify location problems. The complexity of creating meaningful benchmark problems is further raised by including aspects such as deception, epistasis, and related characteristics commonly used to establish the EA hardness of a problem.

At present, we are far from having suitable problem class descriptions and publicly available *representative* benchmark problems on a broad scale. The necessity to collect or generate them is generally acknowledged, though. Beasley's OR library of test problems (1990), available through the Internet from Imperial College in London, is a step in the right direction (http://mscmga.ms.ic.ac.uk/info.html). However, it should be noted that it is extremely difficult to validate the suitability of any finite set of benchmark problems.

F1.2.3.3 Benchmark results

For a meaningful empirical comparison of competing optimization methods comparable statistical data are required. This is far from trivial. Several decisions must be taken in setting up the empirical test.

Choosing the right competitors. The comparison will have only limited significance unless we compare our approach with the strongest competitors available. It can require considerable effort to establish what paradigms should be compared. One reason is that certain very promising new heuristic techniques such as threshold accepting (Dueck and Scheuer 1990, Nissen and Paul 1995) are not widely known, yet. Others, such as tabu search and neural network approaches, have only been tested on a limited subset of classical optimization tasks, although they are potentially powerful in other problem classes as well.

Use results from the literature, or implement all compared paradigms? Implementing each optimization technique and performing experiments on the problem data is a very laborious task. Moreover, precise descriptions of every important detail of all compared paradigms are required. It is frequently difficult to obtain these precise descriptions from the literature. Even worse, as Koza points out in a recent posting to the *GP List*, one usually cannot avoid an unintentional bias in favor of the approach one is particularly familiar with.

However, suitable statistical data cannot in most cases be extracted from the literature. Authors use different measures to characterize algorithmic performance, such as the best solution found, mean performance, and variance of results. The number of runs to obtain statistical data for a given optimization method can vary between 1 and 100 in the literature. Moreover, differing hardware and software makes efficiency comparisons between own data and published results difficult.

Asking authors for the code that was used in generating published benchmark results can also lead to many difficulties related to program documentation, programming style, or hardware and software requirements.

Algorithmic design and parameter settings. There are numerous published variants of EAs, particularly concerning GAs. GAs were originally not developed for function optimization (De Jong 1993). However, much effort has been devoted to adapting them to optimization tasks, especially in terms of representation and search operators. Additional algorithmic parameters such as population size and population structure, crossover rate, and selection mechanism result in a considerable design flexibility for the developer. The same applies, albeit to a lesser extent, to other optimization methods one wishes to investigate.

This freedom in designing the optimization techniques and the difficulty of determining adequate strategy parameter settings adds further complexity to crossparadigm comparisons. It is impossible to test every design option. Additionally, there are different opinions as to whether a fair empirical comparison should focus on the generality of a method over many problem classes, or the power in one specific area of application. Generally, a tradeoff between the power and the generality of a solution technique will be observed (Newell 1969). Baluja (1995), for instance, who disfavors GAs, concentrates on generality. Successful evolutionary approaches, on the other hand, frequently apply a highly problem-dependent representation or decoding scheme and search operators, or they use hybrid approaches that combine EAs with other techniques (see, for example, the works of Davis (1991), Mühlenbein (1989), Liepins and Potter (1991), Falkenauer (1995), and Fleurent and Ferland (1994, 1995)). This leads to the next difficult decision.

Quality indicators for comparisons of optimization techniques. Besides the characteristics of power and generality there are many other aspects of an optimization technique that could be used to assess its quality. Examples include efficiency and ease of implementation. Matters are further complicated in that even the definition and measurement of these quality indicators is not universally agreed upon.

Conduct of the empirical comparison. The general setup of the experiments is crucial for the validity of results. Important decisions include the method of initialization, the termination criterion, and the number of runs on each problem instance.

Besides these difficulties in conducting meaningful empirical comparisons, theoretical results also suggest that it is hard to come to *general* conclusions about advantages and disadvantages of evolutionary optimization.

F1.2.3.4 Implications of the no-free-lunch theorem

Recently, Wolpert and Macready (1995) published a theorem that basically states the following (the no-free-lunch, NFL, theorem): *all algorithms that search for an extremum of a cost function perform exactly the same, when averaged over all possible cost functions.* This result is not specific to EAs but also concerns competing optimization methods.

Some very practical consequences follow from this theorem. They are not really new to optimization practitioners. However, the NFL theorem provides some useful theoretical background.

- The quest for an optimization technique that is generally superior is ill directed, as long as the area of application is not narrowly and precisely defined.
- Good performance of an optimization technique in one area of application will not guarantee equally good results in a different problem area.
- It is necessary to account for the particular biases and properties of the given cost function in the design of a successful algorithm for this application. In other words, one should start by analyzing the problem before thinking about the proper solution technique. Empirical comparisons, however, frequently proceed in the opposite direction, taking some broadly applicable optimization techniques and then looking for suitable test problems.

It is hard to come to general conclusions on advantages and disadvantages of EAs, given the NFL theorem and the difficult empirical situation. The statements in the following section should be taken as the author's subjective view.

F1.2.3.5 Some advantages and disadvantages of evolutionary algorithms

To start with an advantage, it is not difficult to explain the basic idea of EAs to somebody completely new to the field. This is of great importance in terms of practical acceptance of the evolutionary approach.

An advantage and disadvantage at the same time is the design flexibility of EAs. It allows for adaptation to the problem under study, and the breadth of known EA applications gives testimony to this. EAs have in a relatively short time demonstrated their usefulness on an impressive variety of difficult optimization problems, including time-varying and stochastic environments. Algorithmic design of an EA can be achieved in a stepwise, prototyping-like manner. It is easy to produce a first working implementation that can then be improved upon, including domain-specific knowledge and using the 'EA toolbox' mentioned before. This adaptation of the method, however, requires empirical testing of design options and a sound methodical knowledge. In this sense, the many strategy parameters of today's EAs are clearly a disadvantage, as compared to simpler competing optimization methods.

The basic EA types are broadly applicable and, in contrast to many of the more traditional optimization techniques, make only weak assumptions about the domain under study. They can be applied even when the insight into the problem domain is low. In fact, EAs can be positioned along a continuum from weak, broadly applicable methods to strong, highly specialized methods. (Compare also Michalewicz's hierachy of evolution programs (Michalewicz 1996).) Moreover, there are a variety of ways of integrating and hybridizing EAs with other existing methods, as evidenced by numerous publications. These advantages will, however, in general also hold for similar modern heuristics, such as SA or tabu search, even though they might currently lag behind in terms of total research effort spent.

With these competitors EAs also share some disadvantages. First, EAs can generally offer no guarantee of identifying a global optimum in limited time. They are of heuristic character. However, in practical applications it is often not necessary to find a global optimum, but a good solution will suffice. Unfortunately, it is difficult to predict the solution quality attainable with EAs on arbitrary real-world problems in a given amount of time. More generally, the empirical success of EAs is not easily explained in terms of the EA theory available today.

The population approach of EAs usually leads to high computational demands. Since EAs are easily parallelized, this is becoming less of a problem as available hardware power increases and parallel computers are more and more common. Furthermore, the optimization process can be rather inefficient in the final search phase, particularly for GAs. Hybridizing with a quick local optimizer can cater for this problem, though.

With a few exceptions (such as grouping problems), it seems very difficult today to predict in advance whether for a particular real-world optimization problem EAs will produce results superior to those of similar modern heuristics such as threshold accepting or SA. The most important point is really to account for the properties of the problem in designing the algorithm, and here EAs offer a large toolbox to choose from.

F1.2.4 Conclusions

Over the last couple of years, interest in EAs has risen considerably amongst researchers and practitioners in the management domain, although we have not seen the major breakthrough of EAs in practical applications, yet. Most people have been attracted by GAs, while ESs, EP, and GP are not so widely known. GP is the newest technique and is just reaching the level of practical applicability, particularly in the financial sector. Even though GAs are most common, this should not be interpreted as superiority over other EA types. It rather seems to be a good ‘infrastructure’ that contributes to the trend for GAs.

The majority of applications analyzed here concern GAs in combinatorial optimization. Many researchers focus on standard problems to test the quality of their algorithms. The results are mixed. This is partly due to the enormous difficulties associated with conducting meaningful empirical comparisons between optimization techniques. Moreover, the NFL theorem tells us that one should not expect to find a universally superior optimization method. However, the current efforts to develop professional EA tools and parallelize EA applications, and the exponentially growing number of EA researchers, will lead to more practical applications in the future and a better understanding of the relative advantages and weaknesses of the evolutionary approach. Figure F1.2.3 is an attempt to assess the current position of EAs as an optimization method with respect to the technological life cycle.

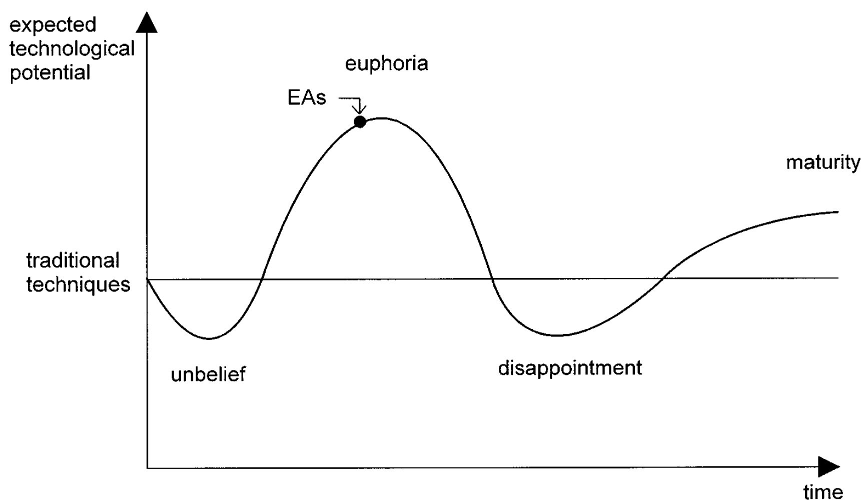

Figure F1.2.3. An estimation of the current state of EAs as an optimization method in a life cycle model as of July 1996.

There is evidence for the robustness of EAs in stochastic optimization where the evaluation involves noise or requires an approximation of the true objective function value (Grefenstette and Fitzpatrick 1985, Hammel and Bäck 1994, Nissen and Biethahn 1995). Encouraging first results have also been achieved in time-varying environments employing nonstandard concepts such as diploidy (Smith 1987, Smith and Goldberg 1992, Dasgupta and McGregor 1992, Ng and Wong 1995). EAs also have been shown to work well on integer programming problems which are presently difficult to solve with conventional techniques such as linear programming for large or nonlinear instances (Bean and Hadj-Alouane 1992, Hadj-Alouane and Bean 1992, Khuri *et al* 1994, Khuri and Bäck 1994, Rudolph 1994).

Currently, EAs are becoming more and more integrated as an optimization module in large software products (e.g. for production planning). Thereby, the end user is often unaware that an evolutionary approach to problem solving is employed. Integrating and hybridizing EAs with other techniques is a most promising research direction. It aims at combining the relative advantages of different problem solving methods and leads to powerful tools for practical applications.

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Appendix A. Tables

Tables F1.2.1, F1.2.2, and F1.2.3 list, respectively, the use of EAs in practical management applications, in application-oriented research in management science, and in other classical optimization problems. The references cited in these tables are listed in Appendix B. In tables F1.2.1 and F1.2.2, the 'Earliest known' column indicates the year of the earliest known presentation.

Table F1.2.1. Practical applications of EAs in management.

Economic sector	Practical application in business	References	Earliest known
1. Industry 1.1 Production	Line balancing in the metal industry	[FALK92] [FULK93b]	1992 1993
	Simultaneous planning of production program,lotsizes, and production sequence in the wallpaper industry	[ZIMM85]	1984
	Load balancing for sugar beet presses	[FOGA95d], [VAVA95]	1995
	Balancing combustion between multiple burners in furnaces and boiler plants	[FOGA88, 89]	1988
	Grouping orders into lots in a foundry	[FALK91b]	1991
	Multiobjective production planning	[BUSC91] [NOCH90]	1991 1990
	Deciding on buffer capacity and number of system pallets in chained production	[NOCH90]	1990
	Production planning in the chemical industry	[BRUN93a]	1993
	Lotsizing and sequencing in the car industry	[ABLA91, 95a]	1989
	Flowshop scheduling for the production of integrated circuits	[WHIT91], [STAR92]	1991
	Sector release scheduling at a computer board assembly and test facility	[CLEV89]	1989
	Sequencing orders in the electrical industry	[ABLA90]	1989
	Sequencing orders in the paper industry	[ABLA90]	1989
	Scheduling foundry core–pour–mold operations	[FULK93a]	1993
	Sequencing in a hot-rolling process	[SCHU93b, c]	1992
	Sequencing orders for the production of engines	[SCHÖ90, 91, 92, 94]	1990
	Scheduler for a finishing plant in clothing	[FOGE96]	1996
	Process planning for part of a multispindle machine	[VÁNC91]	1991
	Stacking of aluminium plates onto pallets	[PROS88]	1988
	Production planning with dominant setup costs	[SCHÜ94]	1994
	Scheduling in car production of Daimler–Benz	[FOGA95a, b], [KRES96]	1995
	Scheduling (assumed: production scheduling) at Rolls Royce (application not confirmed by Rolls Royce)	[FOGA95a, b]	1995
	Sequencing and lotsizing in the pharmaceutical industry	[SCHU94]	1994
	Forge scheduling	[SIRA95]	1995

Table F1.2.1. Practical applications of EAs in management (continued).

Economic sector	Practical application in business	References	Earliest known
1.1 Production (continued)	Production scheduling in a steel mill	[YONG95]	1995
	Slab design (kind of bin packing)	[HIRA95]	1995
	Scheduling and resource management in ship repair	[FILI94, 95]	1994
	Just-in-time scheduling of a collator machine	[RIXE95], [KOPF95]	1995
	Optimizing the cutting of fabric	[FOGE96]	1996
1.2 Inventory	Inventory control in engine manufacturing	[FOGE96]	1996
1.3 Personnel	Crew/staff scheduling	[WILL96]	1996
	Crew scheduling in an industrial plant	[MOCC95]	1995
1.4 Distribution	Siting of retail outlets	[HUGH90]	1990
	Allocation of orders to loading docks in a brewery	[STAR91b, 92, 93a, b]	1991
2. Financial services	Assessing insurance risks	[HUGH90]	
	Developing rules for dealing in currency markets	[HUGH90]	1990
	Modeling trading behavior in financial markets	[SCHU93a]	1993
	Trading strategy search	[NOBL90]	1990
	Security selection and portfolio optimization	[NOBL90]	1990
	Risk management	[NOBL90]	1990
	Evolved neural network predictor to handle pension money	[FOGE96]	1996
	Credit scoring	[NOBL90], [WALK94, 95]	1990 1994
	Time series analysis	[NOBL90]	1990
	Credit card application scoring	[FOGA91, 92]	1991
	Credit card account performance scoring	[FOGA91, 92]	1991
	Credit card transaction fraud detection	[FOGA91, 92]	1991
	Credit evaluation at the Co-Operative Bank	[KING95]	1995
	Fraud detection at Travelers Insurance Company	[KING95]	1995
	Fraud detection at the Bank of America	[VERE95b]	1995
	Financial trading rule generation	[KERS94]	1994
	Detecting insider dealing at London Stock Exchange	[KING95]	1995
	Building financial trading models	[ROGN94]	1994
	Improving trading strategies in stock market simulation	[MAZA95]	1995
	Prediction of prepayment rates for adjustable-rate home mortgage loans	[VERE95a]	1995
	Optimal allocation of personnel in a large bank	[EIBE94b]	1994
	Constructing scorecards for credit control	[FOGA94b], [IRES94, 95]	1994

Table F1.2.1. Practical applications of EAs in management (continued).

Economic sector	Practical application in business	References	Earliest known
3. Energy	Optimal load management in a power plant network	[ADER85], [WAGN85] [HOEH96]	1985 1996
	Optimized power flow in energy supply networks	[MÜLL83a, b, 86] [FUCH83]	1983
	Cost-efficient core design of fast breeder reactors	[HEUS70]	1970
	Optimizing a chain of hydroelectric power plants	[HÜLS94]	1994
	Scheduling planned maintenance of the UK electricity transmission network	[LANG95, 96]	1995
	Network pipe sizing for British Gas	[SURR94, 95]	1994
	Refueling of pressurized water reactors	[AXMA94a, b], [BÄCK95, 96a]	1994
	Scheduling in a liquid-petroleum pipeline	[SCHA94]	1994
	Hot parts operating scheduling of gas turbines	[SAKA93]	1993
	Maximizing efficiency in power station cycles	[SONN82]	1981
	Scheduling delivery trucks for an oil company	[FOGE96]	1996
4. Traffic	Routing and scheduling of freight trains	[GABB91]	1991
	Scheduling trains on single-track lines	[MILL93], [ABRA93b, 94]	1993
	Vehicle routing (United Parcel Service)	[KADA90a, b, 91]	1990
	Finding a just-in-time delivery schedule	[KEME95b]	1995
	Multicommodity transshipment problem	[THAN92b]	1992
	School bus routing	[THAN92a]	1992
	Determining railtrack reconstruction sites to minimize traffic disturbance	[ABLA92, 95a]	1992
	Scheduling cleaning personnel for trains	[ABLA92, 95a]	1992
	Scheduling aircraft landing times to minimize cost	[ABRA93a]	1993
	Predicting the bids of pilots for promotion to larger than their current aircraft	[SYLO93]	1993
	Elevator dispatching	[SIRA95]	1995
	Vehicle scheduling problem of the mass transportation company of Mestre, Italy	[BAIT95]	1995
5. Telecommunication	Designing low-cost sets of packet switching communication network links	[DAVI87, 89], [COOM87]	1987
	Anticipatory routing and scheduling of call requests	[COX91]	1991
	Designing a cost-efficient telecommunication network with a guaranteed level of survivability	[DAVI93b]	1993
	Local and wide-area network design	[KEAR95]	1995
	TSP for several system installers	[KEAR95]	1995
	Optimizing telecommunication network layout	[KEIJ95]	1995
	On-line reassignment of computer tasks across a suite of heterogeneous computers	[FOGE96]	1996

Table F1.2.1. Practical applications of EAs in management (continued).

Economic sector	Practical application in business	References	Earliest known
6. Education	School timetable problem	[COLO91a, b, 92a] [LING92b]	1990 1992
	Scheduling student presentations	[PAEC94b]	1994
	Hybrid solution for a polytechnic timetable problem	[LING92a]	1992
	Timetabling of exams and classes	[ERGU95]	1995
	Exam scheduling problem	[CORN93, 94], [ROSS94a, b]	1993
7. Government	Optimizing budgeting rules by data analysis	[PACK90]	1990
	Automatically screening tax claims	[KING95]	1995
	Scheduling the Hubble Space Telescope	[SPON89]	1989
	Mission planning (two cases)	[FOGE96]	1996
8. Trade	Determining cluster storage properties for product clusters in a distribution center for vegetables/fruits	[BROE95a, b]	1995
	Data mining—analyzing supermarket customer data	[KOK96]	1996
	Optimal selection for direct mailing in marketing	[EIBE96]	1996
	Determining the right quantity of books' first editions	[ABLA95a]	1995
9. Health care	Scheduling patients in a hospital	[ABLA92, 95a]	1992
	Allocating investments to health service programs	[SCHW72]	1972
10. Disposal systems	Optimal siting of local waste disposal systems	[FALK80]	1980
	Vehicle routing and location planning for waste disposal systems	[DEPP92]	1992
11. Military sector	Mission planning	[FOGE96]	1996
	Scheduling an F-14 flight simulator to pilots	[SYSW91a, b]	1991

Table F1.2.2. EAs in application-oriented research in management science. The third column, headed 'No', indicates the number of projects.

General topic	Research application	No	References	Earliest known
Location problems	Facility layout/location planning	10	[KHUR90], [TAM92], [SMIT93], [YIP93], [CHAN94a], [CONW94], [NISS94a, b], [YERA94], [KADO95], [KRAU95], [GARC96]	1990–1996
	Layout design	1	[STAW95]	1995
	Locational and sectoral modeling	1	[STEN93, 94a, b]	1993
	Location planning in distribution	1	[DEMM92]	1992
R & D	Learning models of consumer choice	2	[GREE87], [OLIV93]	1987 1993

Table F1.2.2. EAs in application-oriented research in management science. The third column, headed 'No', indicates the number of projects (continued).

General topic	Research application	No	References	Earliest known
Inventory	Optimizing a Wagner–Whitin model	1	[SCHO76]	1976
	Optimizing decision variables of a stochastic inventory simulation	1	[BIET94], [NISS94a, 95a, b, c]	1994
	Identifying economic order quantities	1	[STOC93]	1993
	Multicriterion inventory classification	1	[GÜVE95]	1995
	Scheduling transportation vehicles in large warehouses	1	[SCHÖ94]	1994
Production	Dynamic multiproduct, multistage lotsizing problem	1	[HELB93]	1992
	GA-based process planning model	1	[AWAD95]	1995
	Minimizing total intercell and intracell moves in cellular manufacturing	1	[GUPT92]	1992
	Line balancing	5	[ANDE90], [SCHÜ92], [BRÄH92], [WEBE93], [ANDE94a, b], [GEHR94], [LEU94], [TSUJ95a, b], [WATA95]	1990–1995
	Knowledge base refinement and rule-based simulation for an automated transportation system	1	[TERA94]	1994
	Short-term production scheduling	2	[MICH95], [KURB95a, b]	1995
	Lotsizing and scheduling	1	[GRÜN95]	1995
	Batch sequencing problem	1	[JORD94]	1994
	Parameter optimization of a simulation model for production planning	2	[AYTU94], [CLAU95, 96]	1994 1995
	Optimization tools for intelligent manufacturing systems	1	[WELL94]	1994
	Flowshop scheduling	17	[ABLA79, 87], [WERN84, 88], [BADA91], [CART91, 93b, 94], [REEV91, 92a, b, 95], [RUBI92], [STÖP92], [BIER92a, 94, 95], [BAC93], [MULK93], [CAI94], [ISHI94], [MURA94], [CHEN95a], [FICH95], [HADI95a, b], [SANG95], [STAW95]	1979–1995
	Job shop scheduling	53	[DAVI85], [HILL87, 88, 89a, b, 90], [LIEP87], [BIEG90], [HÖNE90], [KHUR90], [BAGC91], [FALK91a], [HUSB91a, b, 92, 93, 94], [KANE91], [NAKA91, 94], [NISH91], [BEAN92a], [BRUN92, 93b, 94a, b], [DORN92, 93, 95], [MORI92], [PARE92a, b, 93], [PESC92, 93], [STOR92, 93], [TAMA92], [YAMA92a], [BIER93], [CLAU93], [DAGL93, 95], [DAVI93a], [FANG93], [GEUR93], [GUPT93a, b], [JONE93], [KOPF93a], [UCKU93], [VOLT93], [APPE94], [ATLA94], [DAVE94], [GEN94a, b], [KIM94a], [LEE94], [MATT94], [PALM94b], [SHEN94], [SOAR94], [TUSO94a, b], [CHAN95], [CHEN95b], [CHOI95], [CROC95], [JÓZE95], [KIM95], [KOBA95], [LEE95b, c], [LIM95], [MCMA95], [MESM95], [NORM95], [PARK95c, d, e], [ROGN95], [RUBI95], [SZAK95], [MATT96], [OMAN96]	1985–1996

Table F1.2.2. EAs in application-oriented research in management science. The third column, headed 'No', indicates the number of projects (continued).

General topic	Research application	No	References	Earliest known
Production (continued)	Job shop group scheduling	1	[MAO95]	1995
	Discovering manufacturing control strategies	1	[BOWD92, 95]	1992
	Two-stage production scheduling problem	1	[QUIN95]	1995
	Scheduling in flexible manu-facturing	3	[HOLS93], [FUJI95], [LIAN95]	1993–1995
	Scheduling in a flowline-based cell	1	[JAGA94]	1994
	Optimizing a material flow system	1	[NOCH86, 90]	1986
	Buffer optimization in assembly system	1	[BULG95]	1995
	Evolutionary parameterization of a lotsizing heuristic	1	[SCHW94]	1994
	Optimal network partition and Kanban allocation in just-in-time production	1	[ETTL95], [SCHW95, 96]	1995
	Job scheduling in electrical assembly	1	[DEO95]	1995
	Routing in manufacturing	1	[STAW95]	1995
	Scheduling and resource management in a textile factory	1	[FILI92, 93, 95]	1992
	Scheduling in steel flamecutting	1	[MURR96]	1996
	Scheduling the production of chilled ready meals	1	[SHAW96]	1996
	Sequencing jobs in car industry	2	[DEGE95], [WARW95]	1995
	Scheduling maintenance tasks	1	[GREE94]	1994
	Scheduling problem in a plastics forming plant	1	[TAMA93]	1993
	Scheduling problem in hot-rolling process	2	[TAMA94a], [MAYR95]	1994 1995
	Parallel machine tool scheduling	1	[NORM95]	1995
	Open shop scheduling	1	[FANG93]	1993
	Lotsizing and sequencing in printed circuit board manufacturing	1	[LEE93]	1993
	Decentral production scheduling	1	[WIEN94]	1994
	General production scheduling	5	[FUKU93], [WEIN93], [BLUM94], [PESC94], [STAC94]	1993–1994
	Open-pit design and scheduling	1	[DENB94a, b]	1994
	Underground mine scheduling	1	[DENB95]	1995
	Scheduling solvent production	1	[IGNI91, 93]	1991
	Maintenance scheduling	1	[KIM94b]	1994
	Machine component grouping	1	[VENU92]	1992

Table F1.2.2. EAs in application-oriented research in management science. The third column, headed 'No', indicates the number of projects (continued).

General topic	Research application	No	References	Earliest known
Production (continued)	Design of cost-minimal cable networks for production appliances	1	[SCHI81]	1981
	Grouping parts	1	[STAW95]	1995
	Ordering problem in an assembly process with constant use of parts	1	[AKAT94], [SANN94]	1994
	Information resource matrix for intelligent manufacturing	1	[KULK92]	1992
	Classification of engineering design for later reuse	1	[CAUD92]	1992
	Industrial bin packing problems	1	[FALK92, 94a, b, 95]	1992
	Two-dimensional guillotine cutting problem	1	[PARA95]	1995
	Best-cut bar problem	1	[ORDI95]	1995
Distribution	Vehicle routing	6	[THAN91a, b, 93a, b, c, 95], [LONT92], [MAZI92, 93], [BLAN93], [HIRZ92], [PANK93], [KOPF93b, 94], [UCHI94], [SCHL96]	1991–1996
	Vehicle fleet scheduling	1	[STEF95]	1995
	Transportation problems	4	[CADE94], [YANG94], [GEN94c, 95], [IDA95], [MICH96]	1989–1994
	Minimization of freight rate in commercial road transportation	1	[KOPF92]	1992
	Pallet packing/stacking in trucks	1	[JULI92, 93]	1992
	Assigning customer tours to trucks	1	[SCHR91], [BORK92, 93]	1991
	Optimizing distribution networks	1	[CAST95a, b]	1995
	Two-stage distribution problem	1	[BRAU93]	1993
Strategic management and control	Forecasting of company profit	1	[THOM86]	1986
	Project planning	2	[CHEN94b], [HART96]	1994 1996
	Calculation of budget models	1	[SPUT84]	1984
	Resource-constrained scheduling in project management	1	[LEON95]	1995
	Business system planning	1	[KNOL93]	1993
	Dynamic solutions to a strategic market game	1	[BOND94]	1994
	Portfolio optimization	1	[ABLA95b]	1995
Organization	Evolution of organizational forms under environmental selection	1	[BRUD92a, 93]	1992
	The relationship between organizational structure and ability to adapt	1	[MARE92a, b]	1992

Table F1.2.2. EAs in application-oriented research in management science. The third column, headed 'No', indicates the number of projects (continued).

General topic	Research application	No	References	Earliest known
Timetabling	Timetable problems	15	[HENS86], [ABRA91], [FANG92], [PAEC93, 94a, 95], [BURK94, 95a, b], [KINN94], [ROSS94c, 95], [FUKU95], [JACK95], [JUNG95], [MACD95], [AVIL95], [ERBE95], [FORS95], [QUEI95], [CILI96]	1986–1996
Trade	Sales forecasting for a newspaper	1	[SCHÖ93]	1993
	Selecting competitive products as part of product market analysis	1	[BALA92]	1992
	Market segmentation (deriving product market structures)	1	[HURL94, 95]	1994
	Feature selection for analyzing the characteristics of consumer goods	1	[TERA95]	1995
	Price and quantity decisions in oligopolistic markets	1	[DOSI93]	1993
	Site location of retail stores	1	[HURL94, 95]	1994
	Solving multistage location problems	1	[SCHÜ95a, b, c]	1995
	Evolution of trade strategies	1	[LENT94]	1994
	Bargaining by artificial agents	1	[DWOR96]	1996
	Analyzing efficient market hypothesis	1	[CHEN96]	1996
	Determining good pricing strategies in an oligopolistic market	1	[MARK89, 92a, b, 95]	1989
Financial services	Bankruptcy prediction	1	[SIKO92]	1992
	Loan default prediction	1	[SIKO92]	1992
	Time-series prediction	4	[GERR93], [EGLI94], [BORA95], [ROBI95]	1993–1995
	Commercial loan risk classification	1	[SIKO92]	1992
	Building classification rules for credit scoring	1	[MACK94, 95a]	1994
	Credit card attrition problem	1	[TUFT93]	1993
	Predicting horse races	1	[PERR94]	1994
	Financial analysis	1	[SING94]	1994
	Stock market forecaster	2	[MOOR94], [WARR94]	1994
	Filtering insurance applications	1	[GAMM91]	1991
	Investment portfolio selection	1	[ARNO93], [LORA95]	1993
	Stock market simulation	2	[ARTH91b], [TAYL95]	1991 1995
	Trading models evolution	1	[OUSS96]	1996

Table F1.2.2. EAs in application-oriented research in management science. The third column, headed 'No', indicates the number of projects (continued).

General topic	Research application	No	References	Earliest
Financial services (continued)	Economic modeling	1	[KOZA95]	1995
	Modeling of money markets by adaptive agents	1	[BOEH94]	1994
	Learning strategies in a multiagent stock market simulation	1	[LEBA94]	1994
	Trading automata in a computerized double auction market	5	[ANDR91, 95], [ARTH91a, 92], [MARG91, 92], [HOLL92b], [NOTT92], [ANDR94]	1990–1993
	Optimized stock investment	1	[EDDE95]	1995
	Evolutionary simulation of asset trading strategies	1	[RIEC94]	1994
	Genetic rule induction for financial decision making	2	[ALLE93], [GOON94, 95b]	1993 1994
	Neurogenetic approach to trading strategies	1	[KLIM92]	1992
	Determining parameters of business timescale (analyzing price history)	1	[DACO93]	1993
	Discovering currency investment strategies	2	[BAUE92, 94a, b, 95], [CHOP95], [PICT95]	1992 1995
	Analyzing the currency market	1	[BELT93a, b]	1993
	Negotiation support tool	1	[MATW91]	1991
Energy management	Finding multiple load flow solutions in electrical power networks	1	[YIN91, 94]	1991
	Clustering of power networks	1	[DING92]	1992
	Forecasting natural gas demand for an energy supplier	1	[SCHO93]	1993
	Unit commitment problem, generator scheduling	5	[DASG93a, b], [SHEB94],[KAZA95], [WONG95a, b, c, 96], [ORER96]	1993–1996
	Optimal arrangement of fresh and burnt nuclear fuel	1	[HEIS94a, 94b]	1994
	Fuel cycle optimization	1	[POON90, 92]	1990
Water supply systems	Designing water distribution networks	5	[CEMB79, 92], [MURP92, 93], [LOHB93], [WALT93a, b, c, 94, 95, 96], [SIMP94a, b], [DAVI95], [SAVI94a, b, 95a, c]	1992–1994
	Pressure regulation in water distribution networks to control leakage losses	1	[SAVI95e, 96]	1995
	Cost optimization of opportunity-based maintenance policies	1	[SAVI95c, d]	1995
	Pump scheduling for water supply, minimizing overall costs	1	[MACK95b]	1995
Traffic management	Optimizing train schedules to minimize passenger change times	2	[NACH93, 95a, b, c, 96], [WEZE94], [VOGE95a, b, c, d]	1993, 1994
	Scheduling underground trains	1	[HAMP81]	1981
	Scheduling urban transit systems	1	[CHAK95]	1995
	Elevator group control	1	[ALAN95]	1995

Table F1.2.2. EAs in application-oriented research in management science. The third column, headed 'No', indicates the number of projects (continued).

General topic	Research application	No	References	Earliest known
Traffic management (continued)	Controlling free flying for aircraft	1	[GERD94a, b, c, 95]	1994
	Air traffic free routing	1	[KEME95a, c], [KOK96]	1995
	Solving air traffic control conflicts	1	[ALLI93]	1993
	Partitioning air space	1	[DELA94, 95]	1994
	Airline crew scheduling	1	[CHU95]	1995
	Public transport drive scheduling	1	[WREN95]	1995
	Control of metering rates on freeway ramps	1	[MCDO95b]	1995
Personnel management	Employee staffing and scheduling	3	[EAST93], [LEVI93a, b, 95, 96], [TANO95]	1993–1995
	Talent scheduling	1	[NORD94]	1994
	Audit staff scheduling	1	[SALE94]	1994
Telecommunication	Terminal assignment in a telecommunications network	1	[ABUA94a, b]	1994
	Minimum-broadcast-time problem	1	[HOEL96a]	1996
	Finding investigator tours in telecommunication networks	1	[HOEL96b]	1996
	Analysis of call and service processing in telecommunications	1	[SINK95]	1995
	Routing in communication networks	1	[CARS95]	1995
	Design of communication networks	1	[CLIT89]	1989
Miscellaneous	General resource allocation problems	2	[SCHO76], [BEAN92a]	1976 1992
	Forecasting time series data in economic systems	1	[LEE95a]	1995
	Investigation of taxation-induced interactions in capital budgeting	1	[BERR93]	1993
	Adapting agricultural models	1	[JACU95]	1995

Table F1.2.3. EAs in other classical optimization problems.

Standard problem	References
Traveling salesman problem	[ABLA79, 87], [BRAD85], [GOLD85], [GREF85b, 87b], [HENS86], [JOG87, 91], [LIEP87, 90], [MÜHL87, 88, 91b, 92], [OLIV87], [SIRA87], [SUH87a, b], [WHIT87, 91], [FOGE88, 90, 93c, d], [HERD88, 91], [GORG89, 91a, b, c], [NAPI89], [BRAU90, 91], [JOHN90], [NYGA90, 92], [PETE90], [AMBA91, 92], [BIER91, 92b], [ESHE91], [FOX91], [GROO91], [HOFF91b], [MAND91], [RUDO91], [SENI91], [STAR91a, b, 92], [ULDE91], [BEYE92], [DAVI92], [MATH92], [MOSC92], [YAMA92b], [BAC93], [FOGA93], [HOMA93], [KIDO93], [NETT93], [PRIN93], [STAN93], [SYSW93], [TSUT93], [YANG93a], [BUI94a], [CHEN94a], [DARW94], [DZUB94], [EIBE94a], [TAMA94b], [TANG94], [TATE94], [VALE94], [YOSH94], [ABBA95], [BIAN95], [COTT95], [CRAI95], [JULS95], [ROBB95], [KURE96], [POTV96]

Table F1.2.3. EAs in other classical optimization problems (continued).

Standard problem	References
Iterated games (mostly prisoner's dilemma)	[ADAC87, 91], [AXEL87, 88], [FUJI87], [MARK89], [MILL89], [MATS90], [FOGE91, 92a, 93a, 94, 95a, b], [LIND91], [MÜHL91c], [BRUD92b], [CHAT92], [KOZA92a, b], [STAN93], [SERE94], [DAWI95], [SIEG95], [BURN95], [DARW95], [HART95], [HAO95], [YAO95b], [HO96], [JULS96], [MICH96]
Bin packing	[FOUR85], [SMIT85, 92b], [DAVI90, 92], [KRÖG91, 92], [FALK92, 94a, b, 95], [CORC93], [REEV93], [HINT94], [JAKO94a, b], [KHUR95]
Steiner problem	[HESS89], [GERR91], [HESS91], [OSTE92, 94], [JULS93], [KAPS93], [KAPS94], [ESBE95], [VASI95]
Set covering	[REPP85], [LIEP87, 90, 91], [SEN93], [SEKH93], [BEAS94], [CORN95], [BÄCK96c]
Quadratic assignment problem	[COHO86], [BROW89], [MÜHL89, 90, 91a], [LI90], [HUNT91], [MANI91, 95], [BEAN92a], [COLO92b], [LI92], [NISS92, 93a, 94a, c, d, e], [POON92], [FALC93], [TATE95], [YIP93, 94], [BUI94b], [FLEU94], [KELL94], [MARE94a, b, 95]
Assignment problems	[CART93a], [LEVI93c]
Knapsack problems	[HENS86], [GOLD87], [SMIT87, 92a], [DASG92], [GORD93], [THIE93], [KHUR94a], [MICH94], [NG95], [BÄCK96b]
Partitioning problems	[LASZ90, 91], [COHO91a, b], [COLL91], [HULI91, 92], [JONE91], [DRIE92], [MARU92, 93], [MÜHL92], [LEVI93a, 95, 96], [INAY94], [KHUR94d], [HÖHN95], [KAHN95], [MENO95], [BÄCK96b]
Scheduling (general)	[SANN88], [HOU90, 92], [LAWT92], [SMIT92c], [KIDW93], [ADIT94a, b], [ALI94], [ANDE94a], [CHAN94b], [CORC94], [GONZ94], [HOU94], [KHUR94d], [PICO94], [SCHW94], [SEIB94], [WAH95]
Graph coloring	[DAVI90, 91], [EIBE94a], [COST95], [FLEU95, 96]
Minimum vertex cover	[KHUR94b, c]
Miscellaneous graph problems	[BÄCK94, 96b], [PALM94a], [ABUA95a, b, 96], [PIGG95]
Mapping problems	[MANS91], [NEUH91], [ANSA92], [SOUL96]
Maximum clique problem	[BAZG95], [BUI95], [FLEU95b], [PARK95a, b]
Maximum-flow problem	[MUNA93]
General integer programming	[ABLA79], [BEAN92b], [HADJ92], [RUDO94]
Satisfiability problem	[JONG89], [FLEU95b], [HAO95], [PARK95a, b]
Routing problems	[LIEN94a, b], [MARI94]
Subset sum problem	[KHUR94d]
Query optimization	[YANG93b], [STIL96]
Task allocation	[FALC95]
Load balancing in a database	[ALBA95]

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Classical Optimization Theory: Constrained Optimization (Equality Constraints). 1. Preliminaries. Framework: â€“ Consider a set A