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Recent developments in operations research: A personal perspective

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Abstract

At the 25th anniversary of ORiON it is appropriate to look at the advances in OR during the last 25 years. This paper focuses on what has happened on the international front — there is not a focus on OR developments in South Africa as such. By doing this two observations immediatly follow. Firstly, there have been very few new techniques or tools developed over this period. The classic tools and main techniques of OR are still what they were 25 years ago although vast developments and extensions of these have occurred. Secondly, OR practice has extended into almost all industries as well as all areas of human activity. It is almost impossible to highlight all these advances and give a comprehensive overview — an endeavour has rather been made to give a personal perspective on some of these advances.

Key words: Operations research, problem structuring, community OR, supply chain management, revenue management, metaheuristics, OR in sport.

1 Introduction

The field of *operations research* (OR) originated in the period immediately prior to and during the Second World War (Kirby 2003). It took some years after the war before operations researchers started organising themselves into professional societies and formal OR journals were established around the same time. The first book on OR was published by Morse & Kimball in 1951 (Morse & Kimball 1951). The *Operations Research Society of America* (ORSA) was established during the early 1950s, with the first edition of the flagship journal of ORSA, *Operations Research*, published in 1952. This journal celebrated its 50th anniversary in January 2002. In September 2008, the Operational Research Society of the United Kingdom celebrated its golden anniversary conference at the University of York (Brailsford *et al.*, 2009). The *International Federation of Operations Research Societies* (IFORS) celebrates its 50th anniversary in 2009. The above-mentioned events are history in the making, with OR being around for over 60 years. The history of OR has been captured in numerous ways. Examples are two books on the work done during the Second World War authored by Waddington (1973) and Kirby (2003), with Gass and

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Assad (2003) publishing an annotated history of OR. Many societies and journals have been celebrating this history over the past few years.

It is fitting that the *Operations Research Society of South Africa* (ORSSA) celebrated its 40^{th} year at the 2009 annual conference, having been founded in November 1969. ORSSA established its own journal, *ORiON*, in 1985 and is therefore also celebrating the 25^{th} year of its existence. The papers in this edition of *ORiON* are published to honour and acknowledge this historic occasion in a similar way to many of the more well-known international OR journals.

So what has happened in OR over the past 25 years since the launch of *ORiON* — has there been any growth, and if so, what can be highlighted? In general, the field of OR has grown substantially over the past 25 years, as is evident from the growing number of journals, papers being published and the wide range of books on various OR-related topics. It is almost impossible to cover all that has happened in the field over this period. This paper will therefore provide but a snapshot of recent advances in OR, with a very strong bias towards developments the author is familiar with and has been exposed to in one way or another. In essence, it will therefore be a personal perspective, aiming to cover some of the advances, but in no way claiming to be all-encompassing.

This paper is structured in the following way. Initially reference is made to the introspection OR has gone through over many years and how this has been dealt with. The way operations researchers can contribute to decision-making is briefly discussed. The 'travelling salesman problem' is then used to illustrate the incredible growth in computing power that has taken place and the impact of this on solving larger problems. *Problem structuring methods* (PSMs) and community OR are briefly discussed as relatively new developments over the past 25 years. Two areas where there have been considerable advances are supply chain management and revenue management, while developments in heuristics are also dealt with. Lastly, the practice and use of OR in sport is highlighted.

2 Literature review

There are hardly any articles on the topic of "Recent Advances in OR." Most articles focus on one specific technique or methodology and this illustrates the specialisation that has taken place in the discipline. It also shows the scope of the discipline, making it very difficult for one person to have a complete overview of all aspects relating to OR. In the anniversary edition of *Operations Research,* Haley (2002) is the only author who covers OR in general, although it is a historical perspective on the first 25 years of OR in the UK. All the other papers in this edition are dedicated to a specific topic in OR of which the authors are generally experts. The same holds true for the papers in the *Journal of the Operational Research Society,* published in May 2009, which were published to celebrate the golden anniversary conference of the society. The only exception is the article by Rosenhead (2009) where he reflects on 50 years of OR. Two observations from this paper are interesting: Rosenhead observes that "*it is a sobering thought that there is no major technical field since computer simulation in the early 1960s, which predominantly originated with work carried out outside of the United States.*" Secondly, he highlights the development of two new notable fields within the UK during the 1980s, namely PSMs, often referred to as "soft OR," and community OR. As an active participant and big proponent of both these two developments, his views are not surprising and he even admits that he is "an inherently unreliable witness." It is nevertheless true that PSMs and community OR have both flourished, especially in the UK, over the past 25 years, but at the same time have remained a small part of OR practice worldwide. Rosenhead also relates and reflects on "the ups and downs" of OR under different UK governments and comments on the differences between OR as practiced in the UK and the USA. The latter is more technically oriented, while in the UK there is an inter-play between academic and practical work. In general, these observations are true and the situation in the UK possibly reflects OR in the rest of the world.

What the author has noticed over the past 25 years is that there have been many advances in refining OR techniques and tools by expanding, generalising and making them more applicable for certain problem areas, or for addressing problems that the technique could not be used for in the past. Specialisation around a technique or tool has become the norm that has led to in-depth knowledge and know-how of such techniques and tools. See, for example, Golden *et al.* (2008) where advances in vehicle routing are discussed and Burkard *et al.* (2009) focusing solely on the assignment problem. In this regard almost no entirely new major techniques have been developed. The emphasis has been on advances in application areas and in identifying areas where OR has not been applied in the past. Hand-in-hand with these developments there has been an explosion in the sophistication and technical complexity of computer technology with the increase of computing power. This has allowed solving problems faster, tackling larger problems that are data-rich, and also problems previously considered impossible to even contemplate attempting to address, let alone solve. Where OR originated in the defence environment, it can now be stated that OR is applied in virtually all walks of life. Applications abound in health, forestry, telecommunications, crime prevention, sport, airlines, the environment and various other industries.

3 OR — Critical assessments and challenges

There was a period when operations researchers worldwide were questioning the basic foundations of the discipline. The following statement captures some of the sentiments expressed during the time of reassessment — the authors describe what happened to OR: "*It is not everyone born during a world war, pronounced dead at age 41, only to go through a mid-life crisis and simultaneously be the subject of a post mortem 8 years after, that still develops a plan for the next decade the following year, and even has his or her existence proved another three years later as if nothing happened*" (Corbett *et al.*, 1993).

Articles published were very critical of the OR process and OR people were outspoken about the lack of a future for the discipline — see for example, Dando *et al.* (1977), Hall and Hess (1978), Ackoff (1979), Rowse (1981) and Jackson (1982). The reality is that through much soul-searching about the limitations and assumptions of OR, a richer and deeper understanding of OR and its process came about. This criticism and the associated continuously persistent inward-looking habit have basically disappeared. There is a strong focus, on the one hand, on extending the theoretical basis of many of the OR tools and, on the other, on extending the practical use of OR much more broadly.

An important insight and the outcome of this soul searching was the realisation that the use of OR is not well understood; OR is very difficult to describe. People grappled with how to efficiently and effectively market the profession of OR to the outside world. This prompted the "*Science of Better*" campaign of INFORMS (Horner 2003). Other societies followed with similar efforts. The focus was on communicating or marketing the value of OR in a much more understandable way through, *inter alia*, practical, everyday examples. In 2003 Cook, the then INFORMS President, stated: "*The lack of awareness about who we are and what our value proposition is among our customers is the most critical obstacle to the exploding growth of our profession*" (Horner 2003). The OR fraternity finds it almost impossible to do away with the words "operations research." which is possibly one of its major drawbacks. Through proper "story telling" of real-life examples, this has been overcome to a large extent.

Increasingly, OR professionals are using terms such as "doing good with good OR" to sell themselves and what they do. All these efforts seem to have had the desired effect. The awareness of how one should go about marketing the profession has been invaluable. The use of OR has indeed "exploded" and many analysts are using OR tools and techniques without even realising that they are, in fact, practising OR.

4 Solving real-world problems

Over the past 25 years, it has become possible to solve more complex and larger optimisation problems, as well as heuristics, much faster. This has been due to much improved computer code and algorithms that have been developed together with the exponential growth in computing power and speed. Solving linear programming problems is used to illustrate this point. Bixby (2002) gives a very clear outline of the evolution of computational linear programming since 1987. Not only were tools such as MPSX/370 limited, but these codes could not deal with issues such as degeneracy. While significant progress was made with development on the algorithmic side, there were also advances in computers, which had an enormous effect on the practical application of linear programming. Both the speed of computers and the computer memory capacity have increased dramatically. A new solver, CPLEX, was developed and today it is possibly the most well known code for solving large, linear programming problems. Bixby (2002) states that: "*The numbers speak for themselves. Three orders of magnitude in machine speed and three orders of magnitude in algorithmic speed add up to six orders of magnitude in solving problems. A model that might have taken a year to solve 10 years ago can now solve in less than 30 seconds.*"

To illustrate this point further it is interesting to consider one of the classic problems in OR, namely the *travelling salesman problem* (TSP). It has attracted the attention of mathematicians and computer scientists specifically because it is so easy to describe, yet very difficult to solve. Over the years there have been continuous efforts to solve larger TSP problems faster. The increasing number of cities visited by the travelling salesman illustrates not only the improvement in the power of computers, but also the advances in the algorithms and the programming code used. Applegate *et al.* (2008) solved the TSP to optimality for 85 900 cities. Solving such a large TSP would have been impossible if it were not for the computing power and sophisticated algorithms used. These advances now allow many other complex, large and data-rich problems, which operations researchers would not have bothered to even consider 25 years ago, to be tackled and solved.

5 Decision-making

In essence, OR is all about making better and more informed decisions. Over the entire history of OR, researchers have endeavoured to assist decision-makers through the use of quantitative methods, tools and problem structuring methods to improve their ability to make more informed decisions (Rivett, 1994). An immense amount of learning has taken place about the process of decision-making and in return, many of the existing tools, methods and methodologies have been further developed, adapted and extended. All of us are confronted with making decisions on a daily basis. Some decisions impact and shape our lives, while others hardly have any impact. Nevertheless, making the right choices is a fundamental life skill, relevant to everyone. Made consciously or subconsciously, with good or bad consequences, decisions represent the fundamental tool we use in facing the opportunities, the challenges and the uncertainties of life.

Hammond *et al.* (1999), internationally recognised researchers and experts in the field of decision-making, have distilled from their research the essence of how decisions should be made. This has been a major advance in making the process more usable and understandable to decision makers themselves as well as to the layman. According to them an effective decision-making process fulfils six criteria, namely:

- Focusing on what's important;
- Being logical and consistent;
- Acknowledging both subjective and objective factors and blending analytical with intuitive thinking;
- Requiring only as much information and analysis as is necessary to solve a particular dilemma;
- Encouraging and guiding the gathering of relevant information and informed opinion; and
- Being straightforward, reliable, easy to use and flexible.

They believe that even the most complex decision can be analysed and resolved through considering eight elements that constitute this approach. Each of these keys to effective decision-making can be described as follows:

- *Work on the right decision problem.* What you need to decide is the essence!
- *Specify your objectives.* Your decision should get you where you want to go;
- *Create imaginative alternatives.* Your alternatives represent the different courses of action from which you have to choose;
- *Understand the consequences.* How well do your alternatives satisfy your objectives?

- *Grapple with your trade-offs.* As objectives are frequently in conflict with one another, you'll need to strike a balance;
- *Clarify your uncertainties.* What could happen in future and what is the likelihood of it happening?
- *Think hard about your risk tolerance.* When decisions involve uncertainties, the desired consequence may not be the one that actually results; and
- *Consider linked decisions.* What you decide today could influence your choices of tomorrow and your goals for tomorrow should influence your choices of today.

Leading on from this fairly simplistic way of making decisions, an entirely new field of multi-criteria decision analysis (MCDA) or multi-criteria decision-making (MCDM) has developed rapidly over the past 25 years (see, for example, Belton and Stewart (2002)). A multiple criteria decision-making problem arises when multiple factors or criteria exist — sometimes explicitly, sometimes without conscious thought — which need to be balanced but which, at the same time, can be in conflict. The following definition is provided by Belton and Stewart (2002): "*...the expression MCDA is used as an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter.*" Different categories of problems for which MCDA may be useful have been defined and are presented below (see Roy (1996) and Belton and Stewart (2002)):

- The *choice problematique* — to make a simple choice from a set of alternatives;
- The *sorting problematique* — to sort actions into classes or categories;
- The *ranking problematique* — to place actions in some form of preference ordering, which might not necessarily be complete;
- The *description problematique* — to describe actions and their consequences in a formalised and systematic manner;
- The *design problematique* — to search for, identify or create new decision alternatives to meet the goals and aspirations; and
- The *portfolio problematique* — to choose a subset of alternatives from a larger set of possibilities.

The developments and advances in the field of MCDA are continuing, and this research has been invaluable in understanding the process of decision-making and assisting decision-makers solve large and complex problems.

The range of OR tools, methods and approaches that has been developed over the years is very diverse. Where initially these were very quantitatively oriented there has been a realisation that alternative methods including qualitative methods and tools (PSMs) are also required to address the spectrum of problems facing decision makers.

6 Problem structuring methods

In §3, reference was made to critics of OR practice during the 1970s and 1980s. These critics emphasised that OR practice was more than formulating a mathematical model and that optimality was not everything. Many problems could not be solved with the tools and techniques available at the time. The question that re-occurred was how to go about solving problems with very little structure or messy problems (Ackoff, 1981)? Operations researchers (mainly in the UK) started developing methods that became known as PSMs (Rosenhead, 2006; Friend *et al.*, 1997; Checkland, 1981). These efforts endeavoured to find approaches which were more appropriate for addressing less structured problems. Many of these methods were conceived in the late 1960s and during the 1970s. However, it was only during the late 1980s and 1990s that they grew in sophistication and became better known.

PSMs are a broad group of problem handling approaches with the purpose of assisting in the structuring of problems rather than directly solving them. The whole idea with these methods is for them to be participative and interactive in character. These are the methods to address the wicked and messy problems leading to "*the identification of those factors and issues which should constitute the agenda for further discussion and analysis*" (Rosenhead, 1989). An alternative paradigm was therefore established to address problems that were not well suited to optimisation approaches. Rosenhead (1989) gives the characteristics of this paradigm:

- Non-optimising; seeks alternative solutions that are acceptable on separate dimensions, without trade-offs;
- Reduced data demands, achieved by greater integration of hard and soft data with social judgements;
- Simplicity and transparency, aimed at clarifying the terms of conflict;
- Conceptualises people as active subjects;
- Facilitates planning from the bottom up; and
- Accepts uncertainty, and aims to keep options open for later resolution.

Different methodologies were developed and these were suitable for different problem situations. What they all have in common though, is that they all assist in giving appropriate elements of structure to a wide range of problem situations.

The six methodologies discussed by Rosenhead (1989) are the following:

- Strategic options development and analysis (SODA), with its technical component of cognitive mapping;
- Soft systems methodology (SSM);
- Strategic choice, including the analysis of interconnected decision areas (AIDA) (Friend *et al.*, 1997);
- Robustness analysis;
- Metagame analysis; and
- Hypergame analysis.

There are other approaches in the literature, including the analytic hierarchy process (Saaty, 1980), decision analysis (Watson and Buede, 1988), and decision conferencing (Phillips, 1989).

Over the years more methodologies have been developed. One example is Bryson *et al.* (2004) who describe tools to assist in unravelling complexity in decision-making and introduce the theory and practice of causal mapping. Practical guidelines are provided to develop these, both as individuals and in groups. Causal mapping is one of the tools that can be used to clarify a complex problem and to figure out what to do, how to do it and why it should be done. The process of creating a causal map forces one to think very logically about a problem situation.

PSMs have broadened the scope of OR practice. However, their use is not as wide-spread as the originators had hoped for (Rosenhead, 2006). Their uses, and main users, are to a large extent still limited to the UK. Both Checkland (2006) and Rosenhead (2006) refer to the lack of impact in the US OR circles: "*The phrase 'soft OR' is now generally accepted as meaningful in the field of OR, at least in Europe. (In the USA the iron grip of positivism within operations research is much stronger and movement slower)*" (Checkland, 2006) and "*Broadly this will be an account of European and mainly UK developments. There will not be space to examine why it is that professionals and academics in the United States have so far been unwilling to adopt these methods. But as US publications largely turn a blind eye to overseas developments, it is not unreasonable to reciprocate in kind*" (Rosenhead, 2006).

7 Community OR

In parallel with the development of PSMs, particularly in the UK, an increasing number of OR practitioners undertook OR-type work for a wide range of community, voluntary and charitable organisations. The term "community OR" was used to describe these activities (Midgley, *et al.* 2004). Community OR is now seen as a label used to describe the activities of "*a variety of people engaged in the debate and on-going learning about their own and other people's community development practices*" (Midgley *et al.,* 2004). People become involved in these activities basically for two reasons (Midgley *et al.,* 2004):

- People have a desire to contribute to change in communities; and
- Community OR practitioners have a concern with the design of methodologies, processes of engagement, methods and techniques that can be used in the interaction with communities.

Although the term "community OR" was first coined in 1986, it is acknowledged that work in communities had been done prior to that. It has now spread to all the regions of the world, noticeably also into developing countries. Funding for these types of activities has always been a problem and this has possibly limited wider utilisation of this approach.

8 Supply chain management

An area where there has been phenomenal growth is *supply chain management* (SCM). It started out as physical distribution, which evolved into logistics and has now become supply chain management that covers basically the entire organisation. The *Council for*

Supply Chain Management Professionals (CSCMP) defines supply chain management thus and it is possibly the most widely held view of SCM: "*Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies*" (CSCMP 2009). The author believes supply chain management is possibly the most important business function, cutting across the entire company and playing a very important integration role, ensuring no "silo" behaviour in companies. The area of supply chain management is rife with opportunities for quantitative modelling, simulation and optimisation by either modelling or optimising the entire supply chain or components thereof. It has therefore been an area where OR applications of a wide variety have grown significantly over the past number of years.

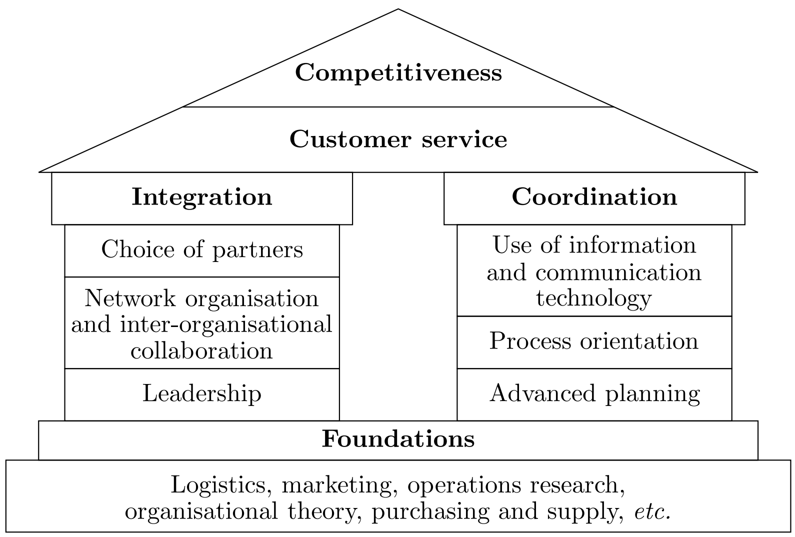

Figure 1: *The house of SCM.*

Figure 1 represents the "house" of SCM as defined by Stadtler & Kilger (2002). From this schematic it is clear that OR is one of the foundations of this "house." The figure also captures the essence of current SCM thinking — companies strive to improve competitiveness and customer service and in so doing endeavour to simultaneously lower costs continuously. The latter is, however, no longer the ultimate goal — lower costs are still important, but it needs to go hand in hand with a consistent, predictable and reliable service. Most of these objectives are achieved through proper integration of the various parties involved; close collaboration is critical. In addition, all the systems of the many parties involved need to be coordinated for materials, information and financial flows to fulfil customer demands.

The simplistic representation of all the elements of a supply chain in Figure 2 (Stadtler and Kilger, 2002) illustrates that with just a small number of manufacturers, this representation of the supply chain can become large and complex. This holds true for many supply chains, such as automotive manufacturing and aircraft manufacturing, which are two very typical examples of extended, large and complex supply chains. Figure 2 shows the main elements of a supply chain that, in many applications, form the basic elements of a quantitative model of a supply chain.

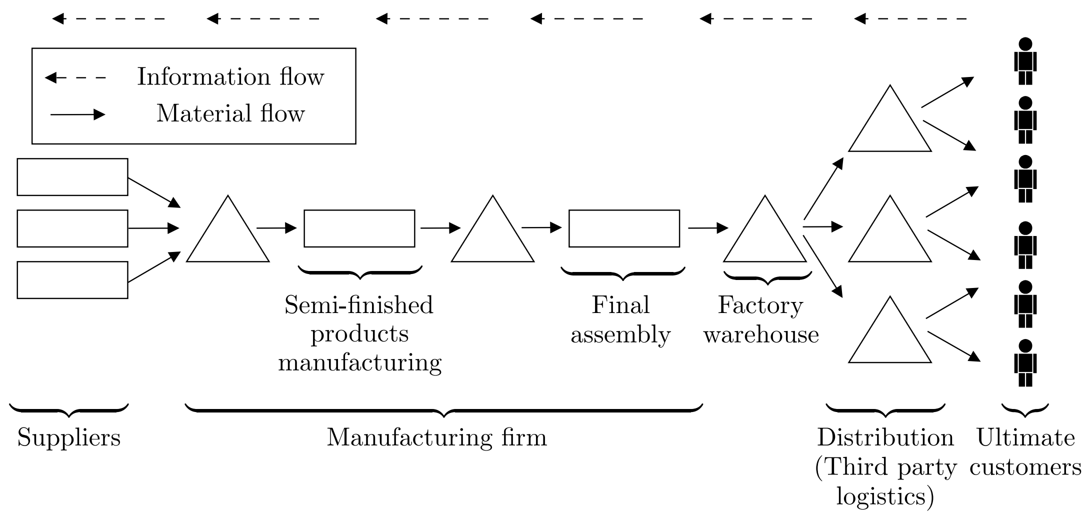

Figure 2: *The main elements of a typical supply chain.*

8.1 Modelling in supply chains

The complexity of supply chains, especially those that involve many suppliers, manufacturing firms, distributors and ultimately hundreds of customers, perhaps cross international borders, necessitates the use of quantitative models to solve the associated problems. Modelling of supply chains, or components of such chains, has received much attention (Shapiro, 2001; Tayur *et al.*, 2002). Many of the winning papers of the prestigious Franz Edelman award of INFORMS over the past number of years are from the logistics or SCM area. It illustrates the fact that through models of the supply chain considerable savings can be obtained. In SCM the tools that have been developed are dedicated to SCM and are called advanced planning systems (APS) (Stadtler and Kilger, 2002). The main APS components are:

- Strategic network planning — determines the configuration of the supply chain;
- Demand planning — medium-term master planning and short-term production and distribution planning;
- Master planning — to determine a production, distribution and purchasing plan;
- Demand fulfilment and *available-to-promise* (ATP);
- Production planning and scheduling; and
- Distribution and transport planning.

All these APS elements are formulated as models that can be and have been solved using OR methods, tools and techniques.

8.2 Reverse logistics

In a world of limited resources, it becomes critical that products such as "white goods" (washing tubs, stoves, fridges, *etc.*) are recovered. This has led to the extension of logistics to include reverse logistics, which incorporates the flow of goods in both directions. This development has a strong element of waste management and sustainable development. Reverse logistics is defined as "*the process of planning, implementing and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain direction for the purpose of recovering value or proper disposal*" (Fleischman, 2001). In traditional "forward" logistics, quantitative models have proved to be powerful supporting tools for these types of decisions. Many standard OR models, such as facility location models, and routing and scheduling models, have been developed. A similar set of standard models to address systematic decision making in this environment is required.

Hand-in-hand with reverse logistics go closed-loop supply chains (Dekker *et al.*, 2004; Stock, 1998). Closed-loop supply chains have traditional forward supply chain activities and a set of additional activities required for the reverse supply chain. For example, mobile phone models change regularly. The older models need to be recovered, sent back, refurbished, recycled and redistributed. These additional activities include (Daniel *et al.*, 2003):

- *Product acquisition* — the activities required to obtain the products from the end users;
- *Reverse logistics* — the activities required to move the products from the points of use to a point(s) of disposition;
- *Test, sort and disposition* — the activities to determine the condition of the products, and the most economically attractive reuse option;
- *Refurbish* — the activities required to execute the most economically attractive option: direct reuse, repair, remanufacture, recycle, disposal; and
- *Distribution and marketing* — the activities required to create and exploit markets for refurbished goods and distribution.

The major difference between closed-loop supply chains and traditional forward supply chains is that in a forward supply chain, the customer is at the end of the processes, and in a closed-loop supply chain, there is value to be recovered from the customer or end-user. The value to be recovered is significant.

8.3 City logistics

Urban freight transport plays a vital role in the sustainable development of cities. There are, however, many challenges facing urban freight transport, including high levels of traffic congestion, environmental impacts, high energy usage and labour problems. Within these conditions, freight carriers are still expected to provide higher levels of service at lower costs. This has led to a new area called *city logistics*, a process to optimise urban logistics with all the difficult conditions that impact urban freight movements (Taniguchi *et al.*, 2001). The work in this area has led to modelling of *city logistics*, demand and supply models, impact models, vehicle routing and scheduling, *etc.*

8.4 Humanitarian logistics

A completely new area of involvement for operations researchers is the area of humanitarian logistics. Logistics plays a huge role in natural and man-made disaster alleviation. The most immediate and critical aspects in such situations are to provide relief to those affected in the form of food, medical supplies, *etc.* Planning for such events is almost impossible since it is not known where and when the next disaster will strike, how many people will be involved and what will be required. Most of this is done by and through humanitarian aid organisations. The whole idea of humanitarian logistics is to introduce private sector logistics or supply chain management thinking into this very complex environment.

Van Wassenhove (2006) and Tomasini (2009) have endeavoured to sensitise those who want to become involved in this area and to bring the private sector closer to all the issues and challenges in the humanitarian space. In this space, humanitarian organisations live by their principles of humanity, neutrality and impartiality, and these principles need to be understood.

Because of the uncertainties involved, preparedness is a priority for humanitarian organisations, as are proper coordination and collaboration with all parties involved. Humanitarian logisticians have strengths since they have shown, through practice, to be agile, adaptive and able to change and set up supply chains quickly and under difficult conditions. While humanitarian logisticians can learn from business, business can learn from them as well. In the whole area of humanitarian logistics there are, however, still many research opportunities to identify how quantitative methods can be of more use.

9 Revenue management

Revenue management (RM) is possibly one of the most successful recent applications of operations research. It can be defined as the maximisation of profit from sales of perishable assets by controlling price and inventory (Yeoman and McMahon-Beattie, 2004). Everyone selling a product or service faces fundamental decisions and is aware of the uncertainties involved. One would like to sell when market conditions are ideal, but at the same time one is not sure what the future will hold. The price must be right — not too low to loose out on potential profits and not so high that the price will put off potential buyers.

The origins of RM can be found in the airline industry where the initial focus was on controlled overbooking, *i.e.* allowing more seats to be sold, because of no-shows of passengers. Airlines needed to fill all their seats on a scheduled flight to maximise profit. Overbooking depends on predictions of the probability distributions of passengers who appear for boarding at flight time, which in turn depends on forecasting of passenger cancellations, no-shows and go-shows (McGill and Van Ryzin, 1999). Airlines then introduced fare products that mixed discount and higher fare passengers in the same compartments. While the lower fare seats ensured the possibility of gaining revenue from seats that would otherwise be empty, it also led to the challenge of how many seats to protect for full-fare passengers. This led to the introduction and development of seat inventory control rules, dictating how many seats should be low fare and how many high-fare seats, and for this airlines need powerful information systems. The real and intense developments of RM started just before deregulation of the airline industry in the USA in 1978. McGill and Van Ryzin (1999) expand on this and list the typical elements of airline RM.

Methods used in RM include mathematical programming, probability theory, forecasting, dynamic programming, *etc.* Talluri and Van Ryzin (2004) provide a comprehensive overview of the theory and practice of RM. The focus is on:

- *quantity-based RM* where the primary demand-management decisions concern product rationing and availability control — how much to sell to whom, whether to accept or reject requests for products, *etc.* These are the core problems of traditional airline RM and are closely related industries such as hotel groups and rental car agencies; and
- *price-based RM* where the primary demand decisions are prices — how to price for various customer groups or how to vary prices over time. Price adjustments, or dynamic pricing, are increasingly using quantitative methods in the estimation of demand functions and the optimisation of pricing decisions. Auctions have also been introduced since they provide an alternative means of dynamically adjusting prices to match market conditions.

RM is traditionally associated with the airline industry, but it has also made in-roads into other service industries such as hotels, restaurants, golf courses, car rentals, cruise lines, movies, *etc.* The emphasis is on providing the right service to the right customer at the right time for the right price.

10 Heuristics and metaheuristics

When confronted with difficult problems to optimise (typically NP-complete or NP-hard problems) approximate techniques are often used to arrive at a good solution. Where optimality cannot be assured, the approximate rule-of-thumb techniques are called heuristic techniques. A heuristic procedure is defined as: "*... for a given problem, a collection of rules or steps that guide one to a solution that may or may not be optimal. The rules are usually based on the problem's characteristics, intention, hunches, good ideas, or reasonable processes for searching*" (Gass and Harris, 1996).

Over the past 25 years the area of heuristic procedures has grown significantly, with an incredible amount of effort and research having gone into it. The CONDOR Report (1988) identified the possibility of heuristic search techniques to be integrated in several ways with optimisation algorithms. This has led to an increased interest and focus on heuristics.

Various types of heuristics have been identified and developed over the years. Holland (1975) identified the link between natural or biological systems and artificial intelligence (AI) on the one hand, and heuristic algorithms on the other. The names of these techniques are closely associated with natural or biological processes. With these developments came another new term, namely metaheuristics, introduced together with "tabu" search (see below). A metaheuristic refers to a master strategy that guides and modifies other heuristics to produce solutions beyond those normally generated in a quest for local optimality. Metaheuristics are therefore higher level strategies and their main aim is to find global optima. As such metaheuristics employ strategies that are specifically designed to avoid or escape local optima.

The use and development of metaheuristics over the past quarter of a century have significantly increased the ability to find very high quality solutions to hard and practical combinatorial optimisation problems in a reasonable time. This is also true for large and poorly understood problems. Metaheuristics are especially being used increasingly in solving complex problems and have enhanced the ability of operations researchers to address such problems. A number of metaheurists are listed below with short descriptions:

10.1 Genetic algorithms

Genetic algorithms (GAs) belong to the evolutionary class of AI techniques. Organisms have biologically evolved to survive and flourish in a changing world. The genetic material of these organisms consists of chromosomes that are divided into genes. The continuation of each species is dependent on their encoding and development. GAs are based on these aspects of evolution. The heuristics need to satisfy the conditions of the fundamental theorem of genetic algorithms (Goldberg, 1989) to move towards optimality.

10.2 Tabu search

Glover (1986) developed a metaheuristic procedure, called *tabu search* (TS), based on strategies used in intelligent decision-making. TS is based on the premise that problem solving, in order to qualify as intelligent, must incorporate adaptive memory and responsive exploration (Glover *et al.*, 1997). Over time the search strategy certain solutions are classified forbidden and they are called tabu (as in *taboo*), so as to avoid cycling during the search process.

10.3 Simulated annealing

Simulated annealing (SA) is a random search technique that exploits the analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system. SA was developed by Kirkpatrick *et al.* (1983) to deal with highly non-linear problems.

10.4 Ant colony optimisation

Ant colony optimisation (ACO) was developed as a result of biologists observing the behavioural patterns of real ants. ACO is a metaheuristic which endeavours to replicate the behaviour of a colony of artificial ants that "cooperate" in finding the shortest path between their nest and a source. Operations researchers have used this metaheuristic to find good solutions to difficult and complex problems (Dorigo *et al.*, 2004).

10.5 Swarm intelligence

Swarm intelligence is a paradigm that also has its origins in nature, noticeably from groups or swarms such as termites, bees, birds in a flock, fish in a school, predators such as a pride of lionesses, *etc.* A swarm can be defined as a group of agents that communicate with each other by acting in their local environment. Agents (birds) within the group (flock) interact to exchange locally available information, which then permeates throughout the group so that the problem of flight direction is solved more efficiently than by a single individual (Engelbrecht, 2005).

11 OR in sport

Sport has world-wide appeal and attracts millions of spectators, mainly through the medium of television. The effect of this is that millions of dollars are poured into sport events through sponsorships and marketing. In the process the athlete and team are earning astronomical amounts of money. Professionalism exists in almost all sport, with coaching the top athlete or team now being the ultimate goal. Improvement in performance not only increases the earnings of the winners but also improves their marketability. Being competitive is the aim of all sport people at all levels.

To be more competitive, enhance performance and improve the level of achievement, science and technology are used in most aspects of sport. Athletes are in better physical condition through improved training and better nutrition. Equipment used is continuously being re-designed, improved and manufactured for close-to-optimal performance. Simultaneously, increasing attention is focused on the psychological aspect of sportsmen and sportswomen. Much effort is also focused on planning game strategies, analysing data as well as analysing the opposition's game plans, tactics and strategies. In addition, a key aspect of sporting events is the ability to generate schedules that optimise logistic issues seen to be fair to all involved. Scheduling is not just restricted to generating fixtures; other aspects such as assigning officials to the games need to be considered as well.

Operations researchers have had an interest in using OR in sport from early on (Wright, 2009). A thorough review of sport applications up to 1976 was given by Ladany and Machol (1977). Since this publication, applications in sport have grown substantially. Scheduling in sport has been one of the main areas of application — see, for example, Kendall *et al.* (2010) and Rasmussen *et al.* (2008). Good schedules have significant financial implications and can have an impact on the performance of every team participating in a tournament. Finding the best schedule is a difficult task as there are multiple decision-makers, constraints and objectives that involve logistical, organisational, economical and fairness issues. Typically, teams play a round-robin tournament where all teams meet one another a fixed number of times. There can be single, double, triple, *etc.* round-robin tournaments. The idea is to construct a schedule or timetable for these tournaments that satisfies a range of constraints or requirements. Various techniques are used to solve these problems, including decomposition methods, integer and constraint programming as well as metaheuristic searches (Kendall *et al.*, 2010). These approaches have been widely applied to a range of different types of sport.

There is also a growing body of literature on tactics and strategy in sport. One of the interesting examples is Clarke *et al.* (1999) who suggest dynamic programming models in cricket, asking the question: "*To run or not to run?*" The South African batsmen, Klusener and Donald, could have used the proposed tactics suggested in this paper during their moment of madness at the Cricket World Cup final in 1999!

Another interesting application in cricket is that of the Duckworth/Lewis method used in determining the winners in limited-overs matches that are affected by rain, bad light or other factors (Duckworth *et al.*, 1998). They used a curve-fitting approach that was not only fair but also understandable enough to be implemented. Duckworth and Lewis are possibly the most well known OR personalities in the world!

12 Other areas of advance

Some application areas have not been covered in this paper, such as quantitative finance or financial mathematics. This has been a very strong growth area over the past decade or so and at many universities, in OR-related departments, financial modelling-oriented courses have been introduced into the curricula. There are many books and articles on this topic and Swart and Venter (2006) give an outline of the basic concepts of quantitative financial analysis. Given the recent economic melt-down which affected financial institutions one can only speculate about the impact and role of these types of financial models. Data mining is another relatively new concept and so is *data envelopment analysis* (DEA), a technique commonly used to evaluate the efficiency of a number of producers — neither of these are afforded any mention in this paper. As OR reaches more and more application areas it becomes increasingly difficult to keep track of this wide spectrum of application areas.

13 Conclusion

It is very challenging to give an overview of advances in OR over the past 25 years. The perspective of one individual has been presented here, which is, of course, limited. Any other operations researcher will have a different view and perspective. Nevertheless, a range of topics with developments over the past 25 years has been presented. A few new methodologies are mentioned; however, the emphasis has been on old applications in new areas and also on extending existing OR methodologies and techniques to solve more complex and larger problems (increasing the number of variables and constraints with much larger data sets as input). It seems that operations researchers are no longer obsessed with the limited basis of OR and with what can be achieved through the use of OR. The emphasis has shifted to increasing the use of OR to all areas of human activity. This author believes that great strides have been made to achieve this; it is becoming difficult to identify where the discipline is being used and to actually identify it as OR! Will OR be around in 25 years from now and in what form? This is difficult to predict. However, the impact of the use of OR techniques and tools, and the scientific approach to problem solving are sure to be felt by many generations to come.

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