THE APPLICATION OF DAI IN THE CONSTRUCTION INDUSTRY

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ABSTRACT: This paper reviews the application of distributed artificial intelligence (DAI) techniques in the construction industry. DAI is concerned with understanding and modelling action and knowledge in collaborative and geographically distributed enterprises. The metaphor of a functionally distributed organisation immediately makes DAI techniques suitable for solving some of the complex problems often encountered in the construction industry. It has been suggested that the industry can learn useful lessons from the application of DAI in other industry sectors such as manufacturing and adapt these techniques to improve collaborative working especially in distributed design environments. This paper reviews the current state-of-the-art and potential applications of DAI in improving collaborative working and distributed decision-making in the construction industry. The study shows that there is limited application of DAI techniques in construction although a number of research projects are now beginning to address it. In contrast, DAI is used for a range of applications in other sectors notably manufacturing, and ideas from DAI are being applied to distributed decision-making in different fields such as: computer-supported co-operative working (CSCW), computer-aided design (CAD) and concurrent engineering. The paper concludes that DAI has many potential applications in such areas as collaborative/concurrent design and management, electronic commerce, and knowledge management in the construction sector. Recommendations for further research in DAI within the construction sector are also included.

KEYWORDS: DAI, Collaborative working, Decision-support, Intelligent agents, Construction industry.

1. INTRODUCTION

The construction process is dependent upon the communication of information. Traditionally this has been done through drawings, but with increasing availability of computational power at reduced costs, there is now the move to 3D Modelling with object orientation, parametrics and data modelling. This development has led to an explosion in demands for improved functionality of IT systems in construction. A typical functional requirement by an architect may include "searching for data/parts, highlighting conflicts between data (e.g. steelwork and services), managing the integration of independently produced specialist data within a model, and managing subsequent changes" (Hitchcock, 2000). In order to meet this demand for improved functionality in construction information systems, it is important to investigate the potential applications of DAI in construction.

DAI is concerned with understanding and modelling action and knowledge in collaborative and geographically distributed enterprises. The two major DAI paradigms are distributed problem solving (DPS) and multi-agent systems (MAS) (Chaib-draa, 1995). In DPS, the user decomposes a problem into co-operative activities, which are then solved using different entities that co-operate to solve the global problem. This is analogous to the way scientists that are distributed in time and/or space, decompose problems and solve them using available expertise (Smith, 1980; Smith and Randall, 1981). However, MAS deals with inherently distributed problems that are defined by a set of units (agents). These agents are autonomous and use different levels of knowledge to reason about their problem domain.

Before going into detailed discussion of the application of DAI in construction, it is important to examine the nature of construction environment that make DAI techniques very suitable for problem solving in the construction domain. These characteristics are summarised below:

- **Distributed information** - design information is often distributed along functional lines and professional activities such as architectural, structural, and building services design.
- **Distributed expertise** - expertise and decision points in construction domain are distributed. This often reflects the different specialist disciplines in an organisation and/or project design and management structure
- **Distributed data sources** - data sources in design are distributed. For example, manufacturing data may be required at design stage before specific components can be designed in detail and incorporated in a project. This requires efficient mechanisms to retrieve information from, or exchange data between, different sources.
- **Diverse professional interests and independent knowledge bases**: Diverse interests often exist in a given construction project and this is normally along the lines of the various professions in the sector (architects, structural engineers, building services - HVAC, and sub-contractors such as steel fabricator, door and window cladding specialists). Consequently, independent knowledge bases are developed based on these functional areas and there is often the need to integrate the independent knowledge bases and improve collaborative working between members of the project team. .

The above outlined characteristics also provide some metrics for assessing the suitability of DAI techniques in a given problem domain.

This paper reviews the application of DAI in construction. It examines the characteristics of construction environments that make them suitable for the application of DAI techniques. It reviews the current state-of-the-art in application of DAI in construction industry and related sectors. The paper gives snapshots of the underlying computing technologies that generally underpin the application of DAI and then discusses other potential application areas and benefits of DAI in construction. The potential barriers that could mitigate against the successful application of DAI in construction are examined and conclusions drawn. Recommendations are given to facilitate the application of DAI in construction. The next section is discusses the current state of application of DAI techniques.

2. STATE -OF- THE-ART

There are research projects that focus on the application of DAI techniques for collaborative design in construction and related sectors. Some of these projects investigate the application of DAI in the form of agent and multi-agent systems. However, there are little or no commercial applications but some of the applications have advanced near such a level. This section discusses some of these applications.

2.1 Applications of DAI in other sectors

The REDUX Server (Petrie 1998) is part of the wider SHARE project at Stanford University USA, that provides a domain-independent decision dependency for a given problem, and can be used to provide co-ordination services for heterogeneous design agents. The PACT project (Cutkosy et al, 1998) demonstrates the application of agents in collaborative distributed design problems (i.e. large-scale concurrent product design) in which the project team members are distributed over multiple sites, cut across various engineering disciplines, and deploy different heterogeneous subsystems. The Co-operating Intelligent Systems for Distribution System Management (CIDIM) was developed as an aid for control engineers to ensure adequate electricity supply to consumers. This project was part of the ARCHON Project - Europe's largest DAI project (Jennings and Wittig 1995). Other DAI - based research projects are discussed in the ensuing section:

GENIAL (Radeke, 1997, 2000; URL3)**:** GENIAL was an EU - funded project under the ESPIRIT programme. The project objective is to facilitate large-scale collaborative engineering by establishing a *Common Semantic Infrastructure* that will enable heterogeneous software systems to communicate and exchange information. It had the following core objectives:

1. To develop an infrastructure that allows networked users, to "acquire, migrate, publish, search, present, and administer information or services equally in an internal network of companies or value-added service providers (Intranet/Extranet), as well as a global network (Internet)",
2. In GENIAL, existing classification systems of the engineers are used to classify the information and the classification is used to search for information over the Internet. These searches include HTML pages and information that remain in legacy data sources (such as databases).

A group of European institutions from industry and academia participated in the GENIAL project as part of the effort to improve engineering design and procurement processes. The partners reflect a cross-sectional representation of users and suppliers of engineering products across different sectors including construction. The high level of industry participation and interest provides for potential commercial applications of GENIAL products.

SHARE (URL4): The SHARE project is an umbrella of different research projects at Stanford University USA. The objective is to provide enabling computing and information processing technologies to teams of people working on product development. This will facilitate collaboration between members of a design team distributed over a wide geographical area. Within the SHARE projects is the Next-Link project that is developing a generic agent and framework that will co-ordinate the work of other engineering agents, especially for design conflict resolution(s) in Electro-mechanical systems.

VENICE (URL5): The project seeks to develop a user-centric cross platform, Internet-based infrastructure for nurturing virtual enterprises. It focuses on four main aspects of virtual entrepreneurship: shared document access, creating virtual teams (and corresponding workspaces), negotiation support, and virtual project management. The project also seeks to build an On-line Bidding System that will create an on-line skills market. Members of the virtual network will have access to details of new opportunities.

CIREP (URL6): This is an EU project funded under the ESPIRIT programme. The aim is to create a WWW information system for component data in the manufacturing sector. The purpose is to create a direct digital link/information flow between component suppliers and the manufacturers. This will enable the suppliers to match specific required components with manufacturers that have them in stock at a given time. In addition, the digital connection will facilitate access to various component data that are provided by the manufacturers.

IMAGINE (URL7): This was an ESPRIT project aimed at providing a multi-agent systems building environment. Such a development environment was expected to support applications in the area of Human Computer Cooperative Work (HCCW). HCCW requires a high level of co-operation among a collection of distributed agents (heterogeneous and/or autonomous) including the human users.

GLOBEMAN21 (URL8): This project is a part of the Intelligent Manufacturing Systems (IMS) programme, a $10bn global research project designed to span over ten years (1995-2005) with a focus on manufacturing industry. Globeman21 had about 37 partners, made up of 21 companies and 16 research organisations that spanned across Australia, Canada, Europe, Japan, and the USA. Completed in March 1999, the project's mission was "to demonstrate how to move the Global Manufacturing practice from rigid supply chain structures into globally distributed, dynamic networks of agile focused enterprises."

2.2 Typical Applications of DAI in Construction

The US Army Corps of Engineers' Construction Engineering Research Laboratory (USACERL) has done work on collaborative engineering design. The ACE project (McGraw et al, 1998), investigated how to support collaboration amongst members of the design team by 'providing an infrastructure for a community of cooperative design agents that assist the users'. Here, agents have areas of specialist knowledge and perform design and checking tasks. They interact directly with a user who is responsible for design changes.

Some work is being done at the Centre for Integrated Facility Engineering (CIFE), Stanford University on the use of agents in a federated collaborative framework (Khedro, 1996) (Khedro, Teicholz, et al., 1994). Pena-Mora at MIT has also investigated the use of intelligent agents in change negotiation (Pena-Mora and Hussein, 1996). Much of the work in the area of automated design has been done on building design support. Systems such as the Lawrence Berkeley Laboratories' Building Design Advisor (Papamichael and LaPorta, 1996) and the Building Design Support Environment (Papamichael and Selkowitz, 1996) rely on expert knowledge residing on one machine, being used solely to advise the user of the consequences of some design choices. The DESSYS Project (URL1) is part of a wider research project - Virtual Reality Design Information Systems (VR-DIS) that is investigating the deployment of multiple software agents to improve collaborative decision-making in a multidisciplinary architectural design environment. The DESSYS research covers knowledge modelling for a decision support system in geotechnical design.

However, a common limitation in the above projects/applications is that the agents do not negotiate amongst their peers to converge on a solution. Since there is no provision for direct negotiation between agents during the design process, the number of designs evaluated remains small. These projects fall short of fully automated collaborative design as most of them rely on human input to suggest design changes and they do not make use of intelligent agents. Hence, convergence to a near-optimal design is dependent on the user and does not make full use of the available computational power, which can allow for the evaluation of many slightly differing designs automatically. There is therefore the need to build on the achievements of these projects and take the research investigations further.

The ADLIB (Agent- based Support for the Collaborative Design of Light Industrial Buildings) project is building on the work done at CERL by placing MAS in a more powerful agent environment (Ugwu et al., 1999a, 1999b, URL2). In the ADLIB project, provision is made for negotiation between agents within a collaborative design environment, and this facilitates the automation of some basic design tasks in the problem domain. The use of agent-based systems in this context is expected to result in increased competitiveness of the construction industry as the decentralisation of complex, large-scale problems and the collaborative input to their resolution, will lead to better quality, more economic, safer and more optimal designs.

3. ENABLING TECHNOLOGIES AND POSSIBLE DAI ARCHITECTURES

The major computing technologies that underpin the application of DAI and facilitate successful application of DAI systems in various sectors are discussed below:

Neural networks (NN): The strategy in NN has been to develop simplified mathematical models of brain-like systems and then to study these models to understand how various computational problems can be solved (Rumelhat et al, 1994). One problem with NN is that the learning process is difficult to model for many practical applications.

Knowledge-based-systems (KBS): These systems model or represent human declarative knowledge in a way that a computer can process and use such knowledge to solve problems. There are based on symbolic processing which is the traditional mainstream approach of AI. The challenge in developing a KBS is how to explicitly model common sense and incorporate the flexibility that characterise human expertise when solving complex problems.

Fuzzy Logic: Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle uncertainty or incompleteness. Zadeh is widely credited as the father of fuzzy logic, and defines it as *a logical system that aims to formalise approximate reasoning* using incomplete data sets (see Zadeh, 1965). Fuzzy logic is best suited to address problems in natural language processing (Zadeh, 1994).

Genetic Algorithms (GA): The basic goal of a GA is to develop systems that demonstrate adaptations that are akin to the Darwinian theory of evolution of biological organisms, in a bid to find optimal combination of decision-making parameters to solve a given problem. In general, most GA employs three primary genetic operators: *Reproduction, Crossover, and Mutation* (see Holland, 1975; Glodberg, 1989).

Case-based reasoning (CBR): Allen (1994) describes CBR as an approach to problem solving based on the retrieval and adaptation of *cases*, or episodic descriptions of problems and their associated solutions. The main phrase in this definition is "*episodic description of problems*" and most CBR research activities revolve around generating and/or formulating an appropriate symbolic representation of problems and their associated solutions at the knowledge level.

Other computing technologies and standards include; Internet Communication Networks, OLE/COM, and Industry Foundation Classes (IFC) etc. However, no single technique addresses the entire problem and challenges that confront the AI research community, and solution to some complex problems often demand a synthesis of more than one technique.

Research on application of DAI systems in construction should explore hybrid solutions to some of the problems in the sector.

There are three basic types of architecture that could be applied to DAI systems. These include:

- **Deliberative**: in which an agent contains an explicit symbolic world model, which develops plans and makes decisions in the way proposed by symbolic AI.
- **Reactive**: in which an agent is capable of reacting to events without complex reasoning.
- **Hybrid Architectures**: that integrates deliberative and reactive agents to develop more robust multi-agent systems.

The distributed nature of the construction process (briefing-design-construction-maintenance and demolition) is inherently complex and difficult for an explicit symbolic representation. On the other hand, reactive architectures implemented in the form of expert systems are generally rigid, limited and inflexible for application in solving construction problems. Consequently hybrid architectures (multi-agent system frameworks) offer great potential to integrate existing (legacy) IT systems and develop Multi-Agent Systems for decision-making in construction.

4. POTENTIAL APPLICATION AREAS AND BENEFITS IN CONSTRUCTION

4.1 Potential application areas in construction

DAI techniques could be applied in the following aspects of design and construction management:

4.1.1 DAI in Design and Project management

Agent-based application is necessary in the following areas in collaborative design:

- Information filtering and retrieval of design/project management data;
- Information customisation to meet the needs of various user in distributed decision-making environments;
- Automation of basic design and project management tasks including negotiation to achieve optimum feasible design. This relieves users from basic mundane tasks so that they can focus their energy on more complex design activities.

4.1.2 DAI in E-Commerce and Supply Chain Management

Another potent application of agents promises to be in E-commerce in construction, in particular Supply Chain Management. In this context the construction process may be viewed as an integrated business for which delivering the right product to the right place, at both the right time and price, is the desired goal (CACM, 1991, 1999; Grosof, 1995). The E-commerce already promises to revolutionise supply chain management by providing networked customers, suppliers, and manufacturers with instant access to the respective data they require for rapid and efficient decision making. From the manufacturer's perspective, rapid and accurate delivery of data/information on construction products will shorten the demand/supply planning cycle and improve productivity[1]. The main attraction here is the currency and reliability associated with such data and the ability of the data/information retrieval mechanisms to break across functional, geographical and enterprise boundaries.

[1] Based on interviews and discussions with a major Civil Engineering Contractor (Customer) and Specialist Door Products Manufacturer (Supplier) in the UK, May 1999.

Hence there is tremendous opportunity for the construction sector to deploy DAI implemented in the form of Intelligent Agents for collaborative supply/demand management between the construction/engineering design team and construction product manufacturers over the Internet. Agent-based systems will have a major role to play in this regard.

4.1.3 DAI in Knowledge Management

Knowledge management at the organisational level is now an area of growing interest. One aspect of the process of knowledge management involves identifying the knowledge associated with a given business process, documenting/storing this knowledge and/or its sources, and then making the documented/stored knowledge available to the workforce. Electronic communication is the most cost-effective means of distributing such knowledge, and organisations in the financial and business sectors are increasingly employing DAI techniques to manage and distribute knowledge among the workforce, and improve overall efficiency/productivity[2]. One potential area that DAI could be applied is on retrieving stored knowledge and procedures of solving problems within a given construction organisation. There is some scope to explore application of DAI in the form of intelligent MAS in co-ordinating knowledge in this industrial context.

4.1.4 DAI in Construction Information Management

There is growing application of intelligent agents in order to manage the problem of information overload on the WWW. The various application areas include; integrated searching over different search engines in the WWW, relevance ranking of documents which can be adapted for user feedback, document analysis, automatic document profile and summary, adaptive user profiling, query expansion and search contexts. The other potential benefit in the application of DAI in information management, is on the 'management of authorised amendments to 3D CAD models and other electronic documents' (Hitchcock, 2000). DAI-based systems could be deployed to manage, control such changes as well as notify changes to the appropriate members of a project team. The application of agents in the above context cuts across the entire spectrum of project life cycles - briefing, design, construction, maintenance and demolition. The construction industry could benefit from deploying agents in such wider context.

4.1.5 DAI in Project Co-ordination

The distributed nature of functions and activities associated with project co-ordination makes it a suitable candidate for application of DAI systems. Some position research papers have reported the potential applications of multi-agent systems for contract bidding, project design, and co-ordination (including supply chain management) using the contract net protocol (Petrie, 1999; Ndumu and Tah, 1998). However, further research work is required to investigate the issues associated with complex co-ordination and negotiation necessary in such wide industrial applications.

4.2 Potential Benefits

Anumba and Newnham (1998) have identified the benefits of DAI in construction as follows:

- **Collaborative and concurrent working**: DAI offers major scope for facilitating collaborative and concurrent engineering in construction. It directly addresses the integration of multi-disciplinary perspectives and provides a framework for resolving design conflicts between members of a construction project;

[2] Demos and technical session presentations by IT Vendors during a Seminar on Knowledge Management - Olympia, London, March 1999

- **Reduction in information overload**: The use of intelligent agents can also help to reduce information overload, and to facilitate interoperability between the many diverse and heterogeneous (legacy) IT systems in the construction industry;
- **Integration of construction expertise**: The distributed problem solving (DPS) allows individual areas of expertise to be encoded into particular agents, thus modelling the real world problem of collaborative and concurrent design development in an intuitive, modular and hence expandable manner. In such an agent-based system as compared with a centralised knowledge-based system, decisions can be taken locally according to local knowledge allowing greater flexibility as this change. Moreover, having agents communicate with each other across the Internet brings greater increases in speed of convergence to a satisfactory design, compared with the traditional inter-disciplinary interactions.

5. POTENTIAL BARRIERS TO APPLICATION OF DAI IN CONSTRUCTION

There are several barriers that need to be overcome in order to facilitate the uptake of DAI in the construction sector. These are discussed under six main sections below:

5.1 Fragmentation of the construction sector

The construction industry is fragmented along professional lines with each profession having its own specialist software stools. This has serious implications in any effort to integrate different heterogeneous software in use at industry level. The problem is further exacerbated by the different formats in which project data is held within the systems. Successful industrial application of DAI requires that distributed software have a common syntax for representation of data within a given domain in order for the systems to be able to exchange data/information in the domain. Although emerging standards such as the XML offer potential solutions to this interoperability problem, the challenges will be more acute in construction.

5.2 Working traditions

Hitchcock (2000) noted that "there is considerable resistance both by management and by users to 'learn' and use even more computer tools, and that some are struggling with basic 2D drafting and the whole issue of drawing on a computer in the first place! Furthermore, whilst the architect hangs on to his 'all singing-all dancing' role, there is a real fear that developments will be limited, apart from those practices of sufficient size to accommodate specialisation. Thus although software houses are now pushing 3D object oriented modelling and 2D drawings will soon become outdated, the construction industry is only coming to terms with 2D CAD". Consequently it is likely there will be greater scepticism in any efforts to explore and deploy the full advantages of DAI.

5.3 Security

Based on assessments of the current state of computing technology, there often exists a lot of commercial sensitivities attached to construction processes. One of the network security issues relates to *wayward agents* that could install viruses, compromise the host, or pilfer through databases. The second security consideration relates to organisational information safety since an unauthorised agent can modify and delete data from a system leading to business failure. Mobile agents, i.e. those that execute on distant machines represent the biggest security risk and consequently most organisations may be reluctant to deploy "*mobile* *agents*" over their networks without adequate guaranteed security [Chess et al 1994; Grosof, 1995; Knapik and Johnson, 1998 pp 250-251; CACM, 1999]. Given sensible access privileges of one's file and interrogation of other machines asking for files, then DAI could receive wider acceptance for collaborative working in construction.

5.4 Safety

There exist some potential legal implications in abdicating responsibility for critical design decisions to autonomous agents that have independent execution autonomy. Machines are still dumb in the sense that they don't have our common sense, and may thus make quite catastrophic decisions in the same unnoticed way a human might make a minor design flaw. DAI systems only provide advice to designers in the same way as consultants do. They are bound to be differences between software advice and consultant's advice but the basic mechanism is the same. Therefore, from practical considerations, *reactive agents* with human-controlled execution may be more acceptable for design applications in the construction industry. This will achieve the twin objectives of giving designers ultimate control in design decisions, whilst facilitating collaboration in the decision-making process.

5.5 Low level of IT Investment and Economic Considerations

The difficulty in quantifying the immediate return on IT investments (economic, productivity and efficiency gains) often makes it difficult to embrace new IT solutions including DAI-based systems. In particular, the headlines and statistics of failed software projects have contributed to the construction industry being very risk-averse with respect to IT investments. On the other hand the dynamic nature of the IT sectors generally demands continuous investment to acquire the necessary IT infrastructure, and improve the skills of the workforce. The construction industry needs to address this problem both in the medium and long-term.

5.6 User Acceptance

The construction industry is generally known to be conservative in its uptake of new technologies. The failure of AI to deliver on some of its previous promises of the 1980s has also contributed to users' reluctance in accepting any new AI/computing technology. This is principally due to the overselling of AI systems (in the early years of knowledge-based systems and expert systems), with regards to their capabilities to mimic human intelligence at solving complex industrial problems. This experience at industry level has resulted in most AI research projects being confined to academic research labs.

6. SUMMARY AND CONCLUSIONS

This paper has reviewed the application of DAI to the construction industry. The paper highlighted that in a construction context, DAI-based systems will facilitate the functions of the various participants in a collaborative project design environment - the architect, structural engineer, building services engineer. It has identified that the potential benefits of DAI include improved collaboration and concurrent working, reduction in information overload, integration of construction expertise. The areas that DAI could be applied to in construction are design and project management, E-commerce and supply chain management, knowledge management, construction information management, and project co-ordination.

It has been shown that there is a considerable scope to apply DAI techniques to the solution of the complex problems often encountered in the construction industry. The pattern of working in construction organisations is naturally distributed based on functional activities and processes. These patterns of working are suitable for research in distributed computing. The problems to address range from improving communication for distributed decision making, to negotiation for collaborative and concurrent design of facilities. Currently, one of the growing common application areas of DAI is in electronic commerce. The other application areas for multi-agent systems are information filtering, and collaborative negotiation between members of a project team. However, one of the challenging problems in developing DAI-systems (such as KBS) remains how to explicitly model common sense and incorporate the flexibility that characterise human expertise. This cognitive activity is a part of the design thought process, and in order to address such limitations, it is essential to investigate a hybrid of computing techniques such as KBS, CBR and GA.

The use of DAI to assist integration of the processes and activities of design, construction planning and management (including component fabrication) will streamline the whole process and result in improved communication between project team members. This means that designers will be able to produce higher quality design solutions by appraising cross-disciplinary impacts of their design decisions. This will in turn reduce design changes and wastage during construction. The concurrent engineering community has pioneered innovative solutions in bringing the downstream concerns such as construction and product maintenance to the attention of designers in the early stages of design and product development. However, although the benefits of improved co-ordination are all too obvious, it remains a challenging task to integrate the activities and processes of design, construction, and management across the functional areas of an organisation.

DAI based research for construction applications needs to address some important issues. These research issues are:

- How to share information between multiple project participants;
- How to coordinate the information sharing;
- How to negotiate between the project participants in order to agree on solution(s) that satisfy the requirements and constraints from various participants;
- How to effectively interface with users for efficient distributed decision making; and
- How to integrate agent-based systems with legacy software systems in use by project team members.

The construction industry needs to take advantage of the opportunities that will arise from greater computerisation, and address the above important issues.

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REFERENCES

Allen B. P. (1994). Case-Based Reasoning Business Applications, *Communications of the ACM*, **37**(3), pp 40 - 42.

Anumba C. J., Newnham L, (1998). Towards the Use of Distributed Artificial Intelligence in collaborative building design; *Proceedings 1st International Conference on New Information Technologies for Decision-making in Civil Engineering,* Miresco E. T. (Ed.), Sheraton Hotel, Montreal, Canada, 11– 13 October 1998, pp.413-424.

Barbuceanu M, Teigen R, Fox M. S, (1997). Agent Based Design and Simulation of Supply

Chain Systems, in *Proceedings of the Sixth Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprise*, June 18-20 1997, Cambridge Massachusetts, USA, pp. 36-41
Chaib-draa, C. (1995). Industrial Applications of Distributed AI, *Communications of the ACM*, 38 (11), pp. 49-53.
Chen P. R; Levesque H. J; Communicative Actions for Artificial Agents in Proceedings of the *First International Conference on Multi-Agent Systems*. AAAI Press/MIT Press, 1990.
Chess D, Harrison C, Kershenbaum A. (1994). Mobile Agents: Are They a Good Idea? *IBM Research Paper RC 19887* – March 16 1995, T. J. Watson Research Center, Yorktown Heights New York.
Clark K. L, Lazarou V. S. (1997). A Multi-Agent System for Distributed Information Retrieval on the World Wide Web, in *Proceedings of the Sixth Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprise*, June 18-20 1997, Cambridge Massachusetts, USA, pp. 87-92.
CACM. (1991). Communications of the ACM **34**(12), *Special Issue on Computer Supported Cooperative Working*, 1991.
CACM. (1994). Communications of the ACM **37** (7): *Special Issue on Intelligent Agents*, 1994.
CACM. (1999). Communications of the ACM **42** (3): *Special Issue on Multi-Agent Systems on the Net and Agents in E-Commerce*, 1999.
Cutkosy M. R, Engelmore R. S, Fikes R. E, Genesereth M. R, Gruber T. R, Mark W. S, Tenenbaum J. M and Weber J. C. (1998). PACT: An Experiment in Integrating Concurrent Engineering Systems, in Readings *in Agents*, Huns M. N, Singh M. P (Eds.); pp. 46-55, Morgan Kaufmann Publishers Inc., USA.
Gilman C, Aparicio B, Barry J, Durnaik T, Ramnath R. (1997). Integration of design and manufacturing in a virtual enterprise using enterprise rules, intelligent agents, STEP, and Workflow, in *Architectures, Networks, and Intelligent Systems for Manufacturing Integration*, (Edited by B. Gopalakrihnan, S. Murugesan, O. Struger, G. Zeichen) Proceedings of SPIE Vol. 3203, pp. 160-171.
Goldberg, D. E. (1989). Genetic algorithms in Search, Optimization and Machine Learning Addison Wesley, USA.
Grosof B. N. (1997). Building Commercial Agents: An IBM Research Perspective, IBM *Research Paper RC 20835* - May 08 1997.
Hitchcock J. (2000). Comments on ADLIB Project Report, *ADLIB Research Report No: ADLIB/01*, October, 1999, **ISBN 1 897911 16 5,** Loughborough University, UK
Holland, J. H. (1975). Adaptation in Natural and Artificial Systems, University of Michigan Press, USA.
Jennings, N.R., Wittig T. (1995). ARCHON: Theory and Practice, D*istributed Artificial Intelligence Theory and Parxis (Avouris N. M and Gasser L Eds.*) pp. 178 - 195, Klumer Academic Publications, London.
Khedro T. (1996). AgentCAD: A Distributed Cooperative CAD Environment, *Information Representation and Delivery in Civil and Structural Engineering Design*, Kumar B. and Retik A. (Eds.), Civil-Comp Press, Edinburgh, 1996, pp 15-19.
Kuokka, D. R, McGuire J, Weba J. C, Tenebaum J. M, Gruber T. R, Olsen G. R. (1993). SHADE: Knowledge-based technology for the Re-Engineering problem, *Annual Paper*, Stanford University, SHADE Documentation Resource page,
McGraw K. D, Lawrence P. W, Morton J. D, Heckel J. (1998). The Agent Collaboration Environment, an Assistant for Architects and Engineers, http://owww.cecer.army.mil/pl/ace.htm
Ndumu D.T.; Tah J.H. M.(1998). Agents in computer assisted collaborative design; AI in

Structural Engineering, Smith I (Ed) *Lecture Notes in Artificial Intelligence No 1454*, 1998, pp. 249-270.
Papamichael K. and LaPorta J. (1996). The Building Design Advisor, *ACADIA96*, Tucson, Arizona, 1996.
Papamichael K. and Selkowitz S. (1996). Building Design Support Environment, *Lawrence Berkeley Laboratory Internal Paper*, 1996.
Pena-Mora F. and Hussein K. (1996). 'Change Negotiation Meetings in a Distributed Collaborative Engineering Environment', *Information Representation and Delivery in Civil and Structural Engineering Design*, Kumar B. and Retik A. (Eds.), Civil-Comp Press, Edinburgh, 1996, pp 29-37.
Petrie C.(1999). Agent-based Project Management. *Lecture Notes in AI – 1500*, Springer-Verlag, 1999.
Petrie C. (1998). The Redux Server, in Readings *in Agents*, Huns M. N, Singh M. P (Eds.); pp. 56 -65, Morgan Kaufmann Publishers Inc., USA.
Radeke E (Ed) (1997). GENIAL _ Global Engineering Networking Intelligent Access Libraries, *GENIAL White Paper*, No.: G_white_paper_V1.0_970805_SNI.doc
Radeke E (Ed)., 2000. 'GEN Global Engineering Networking', Final Report of GENIAL **G**lobal **E**ngineering **N**etworking **I**ntelligent **A**ccess **L**ibraries', EP 22.284
Rumelhat D. E, Widrow B, Lehr M. (1994). The Basic Ideas in Neural Network, *Communications of the ACM*, **37**(3), pp 87 - 92.
Saha D, Chandraskan A. P. (1997). A Framework for Distributed Web-based Microsystem Design, in *Proceedings of the Sixth Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprise*, 1997, Cambridge Massachusetts, USA, pp. 69-74.
Smith R.G, Randall D. (1981). Frameworks for Cooperation in Distributed Problem Solving, *IEE Transactions on Systems, Man, and Cybernetics*, **Vol. SMCC-11** (1), January 1981, pp 61-70.
Smith R.G. (1980). The Contract Net Protocol: High Level Communication and Control in a Distributed Problem Solver, *IEE Transactions on Computers*, **Vol. C-29** (12), December 1980, pp 1104-1113.
Ugwu O. O, Anumba C. J. Newnham, L, Thorpe A. (1999a). Agent-Based Collaborative Design of Constructed Facilities, in 'Artificial Intelligence in Structural Engineering - Information Technology for Design, Manufacturing, Maintenance, and Monitoring', Proceedings of the 6th EG-SEA-AI Workshop, Wierzba 1999, Adam Borkowski (Ed.), Wydawnictwa Naukowo Techniczne, Warsawa, 1999, pp. 199-208.
Ugwu O. O, Anumba C. J. Newnham, L, Thorpe A. (1999b). Agent-Based Decision Support for Collaborative Design and Project Management", The International Journal of Construction Information Technology, Special Issue: Information technology for Effective Project management and Integration, 1999, 7(2), pp. 1-18, Salford University, UK..
URL1 DESSYS Project http://www.ds.arch.tue.nl/Research/Agents/DessysIntro.stm
URL2: ADLIB Project - http://helios.bre.co.uk/adlib
URL3: GENIAL Project - http://www.gen.net/projects/genial.htm
URL4: SHARE Project - http://cdr.stanford.edu/html/SHARE/share.html
URL5: VENICE Project - http://event-net.fi/venice
URL6: CIREP Project - : http://www.codus.co.uk/CIREP/CIREP-1.htm
URL7: IMAGINE Project - http://www.newcastle.research.ec.org/esp-syn/text/5362.html
URL8: GLOBEMAN21 Project - http://ims.toyo-eng.co.jp/
Zadeh L. A. (1965). Fuzzy Sets, Information Control, Vol. 8, 1965, pp 338 - 353.
Zadeh L. A. (1994). Fuzzy Logic, Neural Networks, and Soft Computing, Communications of the ACM, **37**(3), pp 77 - 84.