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Computer-supported conflict resolution for collaborative facility designers

MARCO A. LARA† and SHIMON Y. NOF‡*

Fundamental in engineering design is the notion that collaboration is useful to reduce total project development time and increase design quality. A critical element of collaborative design is the resolution of conflict situations that result naturally from the interaction of cooperating designers, particularly when they are widely dispersed. A multi-approach method for computer-supported resolution of conflict situations in collaborative facility design is introduced. The method is based on social sciences theories used to solve human conflicts. FDL-CR, an extension of the Facility Description Language (FDL) with conflict resolution capabilities provided by the new tool, is the major development in this research. It provides fast identification of the conflict situation, diagnostics of conflict parameters, access to the conflict information by all conflicting parties and mechanisms for conflict resolution. The usefulness of FDL-CR is evaluated with a design case study where a neural-fuzzy inference system is developed to validate the conflict resolution method through the confrontation of conflicting parties. Computer-supported confrontation of conflicting parties was effective when other approaches, such as third-party mediation and persuasion, failed to provide conflict resolution. The new tool is viewed as an essential component of virtual design and manufacturing, and in general e-work.

1. Introduction

Since 1955, approximately 8% of the US Gross National Product (GNP) has been spent annually on new industrial facilities (Tompkins 1997). In addition, existing facilities have been remodelled or expanded to keep up with increasing performance requirements, which, in turn, has resulted in an even larger portion of the US GNP spent on industrial facilities. It is estimated that such investments have accounted for more than US$250 billion per year. Even though facilities planning and design is a topic that has been significantly researched, the fierce competition that is taking place in the global market demands a complete re-orientation in the way facility design projects are approached. Benefits from an effectively planned facility are reduced time for project development and improved design quality. The approach to facilities' planning and design must emphasize the collaborative, simultaneous work of designers, who collaborate on common design projects with differing perspectives and goals. The value of collaboration has been indicated by many researchers (e.g. Nof 1994, 2000). The sequential approach to design project development has proved to be inefficient and costly (Balasubramanian *et al.* 1996, Khanna *et al.* 1998).

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The use of a concurrent (i.e. parallel), multidisciplinary approach to facility design can be valuable to prevent any investment before all deficiencies in the design are anticipated and solved. Implementation of incorrect design or unforeseen design deficiencies may cause damage to the operative and financial stability of a company. Current capabilities of information technology support the development of cooperative information systems and virtual studies for collaborative design. A critical element in collaborative design is the mechanism that coordinates the operation of the network of cooperating (i.e. collaborative) parties, including humans and machines. One of the most important functions of such a coordination mechanism is the ability to detect and solve design discrepancies between cooperating design parties, which occur as a natural consequence of the collaborative design.

Unsolved design discrepancies between cooperating parties may result in costly and possibly hazardous conflict situations at implementation time. A sample of conflict situations that may occur in the physical domain of collaborative facility design are the following:

- overlapping workspace of cooperating robots;
- equipment specifications not meeting production requirements;
- inefficient plant layout;
- field of view of visual sensors not focused on target work points, or obstructed by material-handling equipment, safety devices, or production machinery; and
- work locations inaccessible to material-handling equipment or assembly machinery.

In this research, it is argued that upon the emergence of a conflict situation, the conflict management mechanism should automatically detect and diagnose the conflict, evaluate alternative actions for conflict resolution and select the conflict resolution action to implement. For instance, in the event of the conflict situation 'robot cannot reach the assembly location', potential conflict resolution actions, such as 'relocate the assembly location', 'relocate robot', and 'replace robot', should be instantiated and evaluated by the conflict management mechanism in order to determine which conflict resolution action to implement.

The objective of this paper is to introduce a conflict resolution method and present FDL-CR, the tool developed in our research. FDL-CR (Lara 1999, Lara and Nof 1999a,b) is an extension of the Facility Description Language (FDL) (Witzerman and Nof 1995) with conflict resolution capabilities provided by the new method for conflict resolution. To analyse and evaluate the usefulness of FDL-CR, the most critical part of this conflict resolution method, i.e. confrontation of conflicting design parties, was implemented and validated through several design case studies at different levels of complexity. One of these case studies is discussed in detail to illustrate and explain the analysis and validation.

The paper is organized as follows. In Section 2, the related literature is reviewed. In Section 3, FDL-CR is described along with the method that supports conflict resolution in FDL-CR. Section 4 presents a design case study developed to evaluate FDL-CR's usefulness. Finally, in Section 5, the results of the case study are discussed, and conclusions, including open questions and future research, are presented.

2. Review of related research

Insight for conflict resolution in collaborative facility design is available from diverse sources, which include approaches to conflict resolution in social sciences, computer-supported methods for facility design, conflict resolution in collaborative product design, and computer-supported, multi-approach conflict resolution. In addition, the Facility Description Language (FDL) (Witzerman and Nof 1995) is reviewed since FDL-CR, the development presented here, is an extension of FDL with conflict resolution capabilities supported by the new conflict resolution method.

Surveying the literature on conflict resolution in social sciences helped in the following: (1) to understand the way human disputes, at different levels and domains are solved; (2) to identify useful approaches, e.g. negotiation, mediation and arbitration, which have been successfully applied for solving human disputes; and (3) to learn lessons from proven processes for conflict resolution, such as the US justice system. Surveying the literature on computer-supported facility design helped evaluate the progress in the field and review the knowledge available on computer-supported platforms that support collaborative design in general, and facility design in particular. This survey was important since it revealed the potential impact on the field of design.

Specific topics in conflict resolution in social sciences, computer-supported facility design, conflict resolution in collaborative design, and computer-supported, multi-approach conflict resolution are reviewed next.

2.1. *Conflict resolution in social sciences*

The issue of conflict management is addressed by Fisher (1994) who introduces a set of generic principles for analysing, confronting and resolving protracted social conflicts. These conflicts are defined as expressions of hostility, violence and frustration of basic human needs (e.g. security, recognition and social justice) among interacting groups. Fisher claimed that: (1) conflict analysis (CA) should be undertaken to get insight into the underlying causes of the conflict being addressed; (2) confrontation of conflicting design parties (CC) provides the basis for collaboration and cooperation between involved design parties, and the means for conflict resolution; and (3) conflict resolution (CR) must be part of any decision- and policy-making process defined to prevent and effectively deal with potential conflicts between groups.

The process of compromise/negotiation has serious drawbacks (Labovitz 1980). First, bargaining usually causes disputing parties to assume an inflated position to mitigate any possible loss. Second, the compromise solution may be so weakened at the end of the negotiation process that it will not be effective. Finally, there is often little real commitment by any of the conflicting parties. Labovitz also reports studies that show that effective CR can be achieved both by confrontation of disputing parties and case settlement by an arbitrator, rather than by compromise/negotiation.

Another approach relies on the expertise and discretion of judges and administrators, and it is efficient, effective and often economical (Lan 1997). Lan states that 'conflicts in public administration are normally resolved through the rule of law administered in court, or by way of organizational policies upheld by the chief executive'.

2.2. *Computer-supported facility design*

Early methods of facilities' planning and design have typically focused on the issue of facility layout (Muther 1973, Apple 1977). The advantages and requirements of computer support for facility design were presented by Nof (1979). Some computer-supported method developments for facility equipment selection are as follows.

- FADES (Fisher and Nof 1984), an expert system for equipment selection and facility layout.
- MATHES (Farber and Fisher, 1985), an expert system for selecting material-handling equipment ranging from an automated guided vehicle (AGV) to a gantry crane.
- ROBOSPEC (McGlennon *et al.* 1988), an expert system for selecting industrial robots to work in assembly, material handling and manufacturing facilities.
- Optimization and artificial intelligence approach for robotics equipment selection that matches given task specifications previously defined (Fisher and Maimon 1988).
- KBSES (Kusiak 1990), a knowledge-based system for equipment selection that satisfies technological and financial constraints of the facility plan.

Table 1 shows a sample of computer-based systems for facility design relevant to this research.

Table 1 reveals insight on computer-based systems for facility design. For instance, only the Facility Description Language (Witzerman and Nof 1995, Lara *et al.* 2000) has addressed collaborative facility design. However, an area of opportunity for improvement in FDL is resolution of conflicts among participating design parties. Without this capability, the advantages of computer-supported collaborative design are not fully reached. The critical role of computer-supported conflict resolution in distributed organizations of e-workers has also been discussed by Nof (2000) and Huang *et al.* (2000). The computer-based design developments discussed in table 1 address several functions of facility design, e.g. plant layout, equipment selection and location of resources. To address those aspects of facility design, several computer-based techniques have been used, e.g. expert systems, simulation analysis and fuzzy logic theory.

2.3. *Conflict resolution in collaborative design*

Conflicts in a collaborative design environment occur when at least two incompatible design commitments are made or when a design party has a negative critique of another design party's actions (Klein 1989, 1991, 1993, 1995, Li *et al.* 2000, Sun *et al.* 2001). Klein proposes three underlying concepts.

- Conflicts are hierarchically organized so that the more general conflicts (i.e. domain-independent) are at the upper part of the hierarchy, whereas the more particular conflicts (i.e. domain-dependent) are at the lower part of the hierarchy.
- Conflict solving strategies can be organized in a hierarchy in which the more general strategies are at the upper part of the hierarchy, whereas the more particular conflict-solving strategies are at the lower part of the hierarchy.
- When a conflict occurs, it is assigned a position in the conflict hierarchy to which it belongs, and then it is mapped onto the hierarchy of conflict-solving strategies in order to instantiate a conflict resolution action.

Limitations in conflict-management technology can be overcome if conflict management is viewed as an exception-handling component of an integrated set of cooperating design services, and that design rationale can be captured to help

Research system/model	Main function	Research contribution
CRAFT (Armour and Buffa 1963)	Develops plant layout alternatives	Development of facility layout alternatives based on the pair-wise exchange method
ALDEP (Seehof and Evans 1967)	Locates resources (i.e. machinery and equipment) in a facility layout	Location of resources on the facility floor is based on a relationship chart
CORELAP (Lee and Moore 1967)	Generates facility layout alternatives	It is based on the total closeness rating (TCR) department. TCR is the sum of the numerical values assigned to closeness relationships between a given department and the rest
INDECS (Nof 1979)	Combines database and simulation for the analysis and performance evaluation of a conveyorized facility	A simulation program interacts with a database containing a catalogue of items and equipment (permanent data), and a layout file and control programs
FADES (Fisher and Nof 1984)	Knowledge-based approach to the facility design problem	An expert system solves the plant layout problem by invoking a linear assignment algorithm, selects machinery and equipment that meets production requirements, and develops economic evaluation of production systems
KBML (Heragu and Kusiak 1987, 1990)	Combines knowledge-based and optimization methods for the facilities planning problem	An expert system generates machine layout alternatives and recommends material handling equipment by combining artificial intelligence and optimization techniques. It is linked to a database of models and algorithms for efficient delivery of alternatives
IFLAPS (Tirupatikumara *et al.* 1988)	Generates facility layout alternatives	An expert system builds facility layout alternatives by explicitly specifying interdepartmental, departmental-site, and intersite relationship factors
BLOCPLAN (Donaghey and Pire 1991)	Generates facility layout alternatives	Develops facility layout alternatives based on relationship charts
QLAARP (Banerjee *et al.* 1992)	Improves existing facility layouts	A multi-agent reasoning system improves an existing facility layout by focusing and exploiting a set of qualitative patterns (i.e. facility layout anomalies)
FDL (Witzerman and Nof 1995, Lara *et al.* 2000)	Supports collaborative facility design	Provides a computer-based platform for collaborative work on facility design for a detailed analysis of process layout, flow geometry, visual aspects of control, and safety
FLEXPERT (Badiru and Arif 1996)	Generates facility layout alternatives	An expert system generates facility layout alternatives based on the fuzzy logic theory and the results provided by BLOCPLAN (software for building plant layouts)

Table 1. Sample of computer-based systems for facility design.

design parties identify the reasoning of design actions in order to improve the effectiveness of the conflict-management process (Klein 1995, Cooper and Taleb-Bendiab 1998). A similar approach has been followed in the development of FDL-CR.

Table 2 presents a sample of the developments found through the survey of literature in computer-supported conflict resolution in collaborative design. A summary of the most relevant results of the survey is as follows.

- Systems for different applications in engineering design have been developed. Most address civil and mechanical engineering problems. In addition to table 2, conflict-resolution examples include spatial collision avoidance in multi-robot task allocation (Uchibe *et al.* 2001.) A few systems have been developed for manufacturing and industrial engineering. None addresses explicitly the issue of conflict resolution in collaborative facility design.
- Most of the approaches are based on distributed artificial intelligence in the form of multi-agent systems (MAS). There is no common pattern or trend in the way the MAS organize cooperating design agents to accomplish collaboration (e.g. Huang and Nof 2000). However, the issue of conflict resolution is consistently recognized as an essential function of the MAS coordination mechanism (e.g. Huang *et al.* 2000).
- Definition of the term *conflict* mostly depends on the perspective and issues under consideration. Therefore, there is no unique definition for the term *conflict* within the physical domain of collaborative engineering.
- Aspects of implementation of computer-based systems for conflict resolution in collaborative design (e.g. platforms for collaborative work, data structures and programming languages) are specific to each individual system. However, the most successful implementations are based on platforms that allow distributed, collaborative work, groupware, object-oriented representation of data structures. In some cases the software is written in C++, whereas in other cases it is written in AI programming languages such as LISP or Prolog.
- Conflict-resolution methods are specific to each problem. However, a widely adopted framework is the one proposed by Klein (1995), which is based on a taxonomy (hierarchy) of conflicts, a taxonomy of conflict-solving strategies, and on a mechanism that maps a conflict in the taxonomy of conflicts onto the corresponding conflict resolution strategy in a taxonomy of strategies.

Table 2 reveals that negotiation is a widely accepted approach for conflict resolution in collaborative facility design. However, the issue is to minimize the cost and duration of these negotiations. Another important finding is that existing developments are based on single approaches (e.g. negotiation) to conflict resolution and that no development uses conflict modelling and analysis to attempt an early, cost-effective conflict resolution. Finally, it should be noted that in most of the surveyed developments, conflicts are assumed to be of similar complexity level.

2.4. *Computer-supported multistage conflict resolution*

Some organizations, such as the US justice system, have successfully based the conflict resolution process on multi-approach mechanisms. There are a few computer-supported developments in various domains that rationally group conflict resolution approaches in such a way that, if a given approach fails to solve the conflict situation at hand, another is instantiated. According to Labovitz (1980) and Lan (1997), this concept has been successful in manual practice.

Research work	Main function	Research contribution
(Werkman 1990)	Supports negotiation in MAS	A knowledge-based model of negotiation that includes an arbitrator in the negotiation process to store the agent's perspective and collects the inter-agent dependencies. The arbitrator comprises much of the negotiation knowledge and has the responsibility of mediating between agents when negotiation run into 'deadlock'
(Sycara 1991)	Supports negotiation in MAS	A case-based and utility negotiation to arrive at a compromise solution. The proposed negotiation model embraced several key components: knowledge of previous designs, communication of design rationale, justifications and objections to proposed design solutions, constraint propagation and relaxation, and traversal of goals graphs
AGENTS (Huang and Brandon 1993)	Generates conflict resolution strategies	An agent based system (cooperative expert systems, domain-independent, general purpose, object-oriented, built in Prolog) for conflict resolution
CIC (Oh *et al*. 1993)	Supports collaborative mechanical assembly design	A novel feature of this work is the use of a 3-tier conflict resolution scheme that is based on the negotiation metaphor
Galileo3 (Bahler *et al*. 1994)	A negotiation protocol that detects potentially conflicting decisions between design agents and evaluates the various design plans proposed by the agents	The computer support lies on the provision of feedback to design agents regarding the impact of their design solution plans. Decision-making as to which direction to take after a conflict has been detected relies on the human designer
iDSS (Klein 1995)	Provides CR for collaborative design	The core of iDSS is a service for capturing all process, product, and organizational decisions and their interdependencies
SHARED-DRIMS (Pena-Mora *et al*. 1995)	Supports negotiation and CR	A system that access both the design rationale of individual designers and information about past negotiations. Therefore, the participating designers are provided with information about how and why each decision was made. This information in turn brings out the data needed to minimize conflicts
Schemebuilder (Oh and Sharpe 1995)	Provides an integrated design workbench aiming at supporting the conceptual and embodiment phases of interdisciplinary systems design	Two basic approaches to managing design conflicts: (1) avoid them or minimize their occurrence by designing them away; and (2) resolving them at run-time when they occur
Iterative Design Formalism (Khanna *et al*. 1998)	Formal modeling of distributed design tasks, carried out by distributed, concurrent designers.	An iterative approach based on the task specification graph model enhances parallelism and synchronization to avoid and prevent cooperation conflicts
CONCENSUS (Cooper and Taleb-Bendiab, 1998)	Negotiation support for conflict resolution in concurrent engineering design	A framework prototype for multi-agent negotiations
Construction Space Conflict Resolution (Guo and Wu 2000)	Decision support to resolve conflicts among construction engineers	Criteria and heuristic rules to identify and solve problems in space planning
Concurrent Product Design and Manufacturing Planning (Sun *et al*. 2001)	Conflict resolution and design improvement in design-for-manufacturability	A MAS service approach including one console agent (facilitator) and six design-phases service agents

Table 2. Sample of research on conflict resolution in general collaborative design.

A general negotiation model that solves labour-management disputes is presented by Sycara (1990). PERSUADER, the computer prototype developed by Sycara, consists of three computer-based entities: an entity representing the company's interests, an entity representing the worker union's interests, and a mediation entity. In the event of a dispute between the entity representing the company's interests and that representing the worker union's interests, PERSUADER tries to solve it using negotiation through the mediation entity. If that approach does not work, then persuasion is used in an attempt to achieve conflict resolution. In persuasion, PERSUADER uses belief modification through persuasive argumentation to try to change (increase or decrease) the importance that the disputing entities have attached to the issues involved in the conflict. If conflict resolution is not achieved through persuasion, PERSUADER proceeds to generate modified compromise solutions using a memory of past conflict resolution cases in which modification of compromise solutions were used.

Resolution of conflict situations in cooperative knowledge-based systems is addressed by Wong (1997). In cooperative knowledge-based systems (CKBS), a conflict situation occurs when involved parties make mutually exclusive propositions. BDN (Building Design Network) is the computer development that supports the conflict resolution mechanism introduced by Wong. Connection design, beam design and column design are the construction design activities supported by BDN. BDN is composed of three potentially conflicting parties: a design party, a fabrication party and a construction party. To expedite the conflict resolution process, each operates a knowledge base with information and facts relevant to its field of specialization. BDN provides the necessary infrastructure for communication between the involved parties and high-level protocols for cooperative problem-solving. BDN uses a four-stage mechanism for conflict resolution. The order of execution of the conflict resolution approaches depends on the application domain. The logic is the same as that of PERSUADER's (Sycara 1990) in that if a conflict resolution approach fails to solve the conflict situation, another is instantiated. The conflict resolution approaches supported by BDN are: (1) inquiry: the involved parties collect all the necessary information (i.e. data, beliefs, and facts) with respect to the conflict and restructure their knowledge bases using the collected information; (2) arbitration: conflict resolution is attempted by evaluating competing conflict resolution alternatives and selecting the alternative that will best satisfy a given performance criterion; (3) persuasion: conflict resolution is achieved by redefining the original conflict situation in an effort to narrow the differences between the disputing parties; (4) accommodation: this conflict resolution approach incorporates the 'agendas' of all parties involved in the conflict with the intention of using them in the future. Wong also claims that to guarantee global optimal solutions, a compromise-based conflict resolution approach should be avoided as compromise solutions tend to ignore global optimal solutions in favour of local suboptimal solutions.

A computer-supported, multi-approach mechanism to support resolution of interfunctional conflict situations, which are defined by them as 'the perceived differences in goals and ideologies across independent and interactive functions', is introduced by Xie *et al.* (1998). Several conflict resolution approaches are considered and rationally grouped in the method introduced by Xie *et al.* Like Sycara (1990) and Wong (1997), in this method a conflict resolution approach is instantiated if the previous one fails. The elements of the multi-approach conflict resolution mechanism introduced by Xie *et al.* are: (1) avoidance: the conflict situation is ignored rather than confronted; (2) accommodation: some of the disputing parties yield to the interests of the other parties; (3) competition: some of the disputing parties impose their interests on the other parties by the use of force or coercion; (4) collaboration: all involved entities participate in the conflict-resolution process by collecting and sharing information as well as exploring optimal, global actions; (5) compromise: disputing parties agree to settle their differences at an intermediate point across the gap that separates their positions with respect to the conflict; and 6) hierarchical resolution: the conflict is settled by a hierarchically superior entity, say, an arbitrator, who collects and analyses relevant information associated with the conflict in order to achieve conflict resolution.

Similar approaches have been applied with multi-agent architectures by later researchers (e.g. Cooper and Taleb-Bendiab 1998, Sun *et al.* 2001).

The results achieved by Xie *et al.* (1998) have implications for the design and development of the FDL-CR method for conflict resolution. For instance, the effectiveness of a conflict-resolution approach is contingent upon the level of complexity of the conflict. Xie *et al.* argue that a collaboration approach can be used to solve conflict situations of low complexity, whereas a competition approach can be used to solve conflict situations of relatively higher complexity.

2.5. *Facility Description Language (FDL)*

The collaborative facility design tool is the basis for FDL-CR, and will be reviewed here briefly.

FDL (Witzerman and Nof 1995, Lara *et al.* 2000) is a computer tool that supports distributed facility design and provides solid modelling and 3D simulation–emulation environment for the integrated development and evaluation of facility design models. It provides a framework and common language for the input of geometric and non-geometric information of a facility model. In addition, it provides a means for evaluation of critical design aspects of the facility model. FDL is developed on ROBCAD (Tecnomatix 1998), a simulator–emulator system that has 3D CAD capabilities, collision detection, kinematics modelling, and simulation.

The development of FDL focused on the following four design aspects of a facility model: (1) process geometry: production machinery, robotics equipment and material-handling devices must be able to feed, orient, and position tools and parts; (2) flow geometry: robotics equipment and human operators must be able to access transfer locations and workstations; material-handling devices must have the required capacity (load and speed) and dimensions; storage locations and part-buffers must have the appropriate geometry and capacity; aisles must have enough width to allow the flow of operators and material handling devices; (3) visual aspects of control: operators, vision systems and other line-of-sight sensors must be correctly positioned and oriented with respect to target locations to support production operations; at the simulation–emulation level, visual indicators must provide design parties with a systematic way to observe and diagnose the planned control logic; (4) safety considerations: collisions between machinery, robotics equipment and material-handling devices and equipment must be prevented from occurring, and personnel must be protected from unnecessary exposure to hazards, such as active robot workspaces and moving material handling devices.

The given FDL-user interaction functions are categorized as follows.

- Data entry: the FDL's data entry functions allow direct input of data from design parties into the geometric and non-geometric databases in order to create/modify a facility model.
- Model manipulation: the FDL's model manipulation functions allow design parties to make changes in an existing facility model by updating the corresponding geometric databases.
- Evaluation: the FDL's evaluation functions allow design parties to verify the correctness of various design aspects of the facility model. The evaluation functions supported by FDL are the following:
    - Database reconciliation: this function detects inconsistencies between new data input and current FDL data.
    - Space utilization: this function detects potential collisions between the components (e.g. robotics equipment and material handling devices) of the facility model.
    - Detection of conflict situations in collaborative facility design: this function detects conflict situations relative to the operation of the facility model's components (e.g., device A cannot reach work point B, field of view of sensor X is out of target by Y mm).
    - Constraints: detects when a design violates a given constraint (e.g. vision and safety issues).

The FDL's evaluation functions provide detection of design conflicts by using pre-programmed functions that check several design aspects of the facility model. For instance, robot's reachability with respect to work points and transfer locations, continuity and direction of material flow, and aisle clearances. FDL supports detection of design conflicts in the following areas.

- Material flow depiction (FDL-chk flow): allows design parties to verify visually the flow of parts and other components of the facility model, such as material-handling devices.
- Reach (FDL-chk reach): allows design parties to verify if a component of the facility model, say, a robot can reach and orient with respect to a work point or transfer location.
- Aisle (FDL-chk aisles): allows design parties to verify it the aisles of the facility model have enough clearance for the operation of the material-handling components of the model.
- Field of view (FDL-fov): allows design parties to verify if visual sensors are properly oriented with respect to target work locations and if their fields of view are not obstructed, say, by other components of the facility model, such as a robot or a material-handling device.

FDL can serve as a useful 3D modelling tool for the definition and description of a production facility at different levels of abstraction, allowing the same basic design model to be refined iteratively throughout the development process.

3. Method to support conflict resolution in collaborative facility design

3.1. *Overview*

The operation logic of the new method for conflict resolution is shown in figure 1. The method is based on concepts of conflict resolution in social sciences introduced by Fisher (1994), Labovitz (1980) and Lan (1997), who argue that in contrast with the existing literature on computer-supported conflict resolution, compromise and negotiation are not the ending and deciding elements of the conflict resolution process. Instead, as shown in figure 1, if conflict resolution is not achieved after the first four stages of the process, the arbitration stage, comprised of conflict modelling and analysis, confrontation of conflicting parties, and conflict resolution, will take place. According to Labovitz (1980) and Lan (1997), resolution of conflict situations based on arbitration has been successful in justice administration and public administration systems.

A special feature of the FDL-CR method for conflict resolution is that in each of the five stages of the conflict-resolution process, the outcome of the process is recorded in conflict-resolution casebases owned by the participating design parties. In future conflict resolution endeavors, the knowledge stored in the casebases can be used by them to settle emerging conflict situations.

The data contained in the conflict resolution casebases are related to previous conflict resolution endeavors, for instance, the parties in conflict, the conflict issues (i.e. type of conflict and conflicting parties' arguments) and the solution achieved. This technique has already been followed by Sycara (1991). The data in the conflict resolution casebases may be organized as a knowledge-based system, e.g. following a relational approach with a record in the casebases mapped to a particular conflict situation addressed in the past. Another relevant technique that has been increasingly applied for handling dynamic, distributed engineering and management data and knowledge is workflow modeling and management (e.g. Kim and Nof 2001). A related interesting approach to such knowledge representation and management has been developed (Chomicki and Lobo 1995), with monitors-procedures for history-based policies of event–condition–action rules to identify, resolve or cancel conflicts over distributed networks. The casebases can be indexed by parties in conflict, type of conflict situation, date, etc. Having knowledge available on how conflict situations were settled in the past should expedite the conflict resolution process.

An underlying premise of the method described in figure 1 is that the conflict-resolution process becomes more costly as it advances through the different stages of the process. The same concept is followed in the US justice administration system where the most costly stage is the actual court hearing. In justice administration in the USA, before the hearing session, a mediating party tries to persuade the conflicting parties to narrow their differences and avoid taking the case before a judge, as litigation is a costly and lengthy process. If the mediation process and the counter proposal by conflicting parties fail to settle the case, then inevitably the case will go into the courtroom where a judge will settle the case at the expense of the conflicting design parties.

Another underlying premise in the design and development of the FDL-CR conflict resolution method is prevention of conflict perpetuation and escalation (C_{PE}), which usually occurs when a losing party appeals a decision ruled by an arbitrator, thus bringing the conflict resolution process into an endless loop. This design premise will ensure conflict resolution.

3.2. *Design and implementation details of the method for conflict resolution*

The approaches applied in the five main stages of the conflict resolution process (figure 1) are as follows.

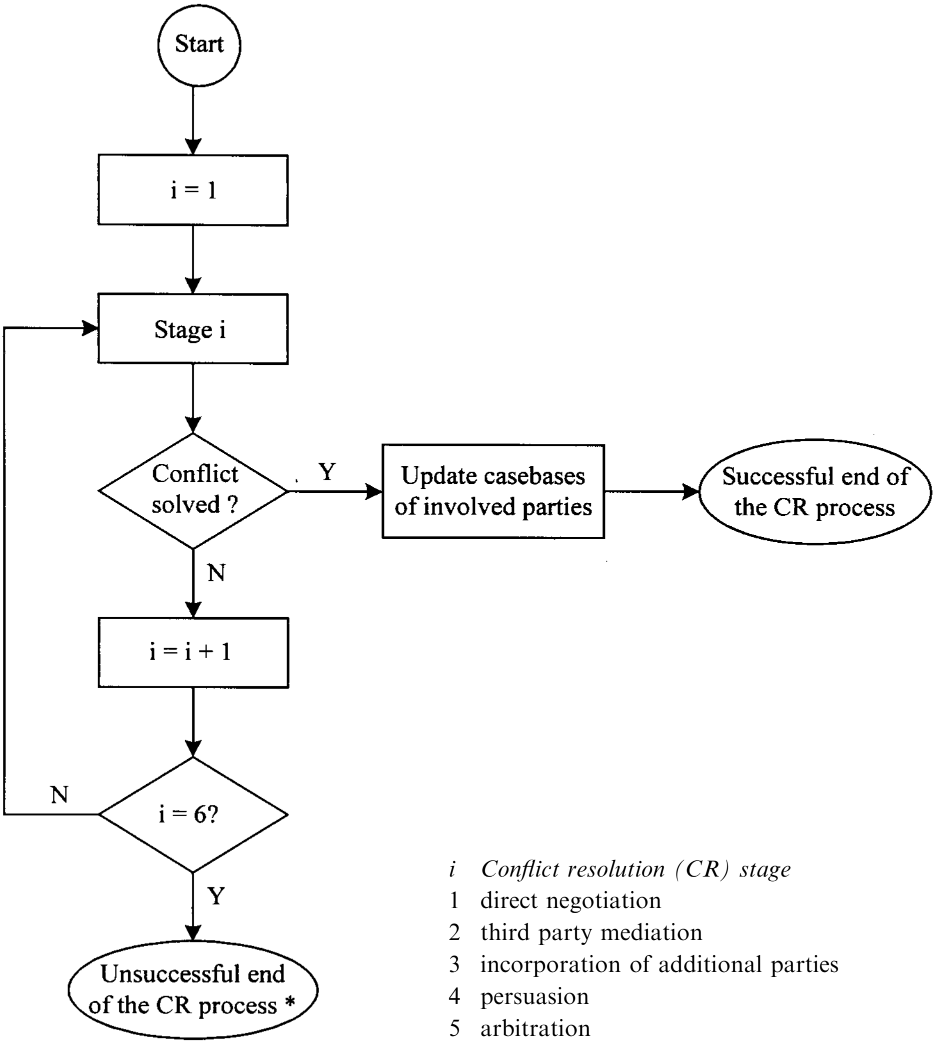

Figure 1. Operation logic of the suggested method for computer supported conflict resolution. * In facility design conflicts, when a resolution is necessary, only if the computerized support fails is human intervention needed.

- *Stage* 1. In the 'negotiation' stage of the introduced conflict resolution method, the involved design parties engage in direct negotiation in order to solve the conflict situation. To proceed with the conflict resolution process, α, the design party that brings about the conflict situation, uses knowledge available in its conflict-resolution casebase to prepare λ_α, a conflict resolution proposal for its opposing parties (β). β use knowledge available in their conflict-resolution casebases to evaluate λ_α. If λ_α is accepted by β, the conflict situation is considered solved, otherwise $\tau(\lambda_\alpha)$, the β's counter proposal to λ_α, is prepared by β and sent to α. If $\tau(\lambda_\alpha)$ is accepted, then the conflict situation is considered solved, otherwise the conflict resolution process advances to Stage 2.

- *Stage* 2. In the 'third party mediation' stage, the mediation party (δ) prepares a conflict resolution proposal (λ_δ) using knowledge available in its conflict-resolution casebase and sends it to the involved design parties. λ_δ is evaluated by them using knowledge available in their conflict-resolution casebases. If λ_δ is accepted, then the conflict situation is considered solved, otherwise the involved design parties prepare and send δ $\tau(\lambda_\delta)$, their counter offer to λ_δ. If $\tau(\lambda_\delta)$ is accepted, then the conflict situation is considered solved, otherwise the conflict resolution process advances to Stage 3.
- *Stage* 3. In the 'incorporation of additional parties' stage, specialized design parties (γ) provide the involved design parties with specialized advice and expertise (λ_γ), which is built on knowledge available in their conflict-resolution casebases. λ_γ is prepared and sent to the involved design parties by γ. If λ_γ is accepted, then the conflict situation is considered solved, otherwise the involved design parties prepare and send γ $\tau(\lambda_\gamma)$, their counter offer to λ_γ. If $\tau(\lambda_\gamma)$ is accepted, then the conflict situation is considered solved, otherwise the conflict resolution process advances to Stage 4.
- *Stage* 4. In the 'persuasion' stage, the mediation party (δ) attempts to persuade the involved design parties to change the importance they have attached to the issues in the conflict in order to achieve conflict resolution. For that purpose, δ sends the involved design parties a set of persuasive arguments. The involved design parties, using knowledge available in their conflict-resolution casebases, evaluate the persuasive arguments. If the persuasive argumentation is effective, then the conflict situation is considered solved, otherwise the conflict-resolution process advances to Stage 5.
- *Stage* 5. In the 'arbitration' stage, conflict modeling (CM) and analysis (CA), confrontation of conflicting design parties (CC) and conflict resolution (CR) are used to solve the conflict situation and to prevent a potential C_{PE}. In CM, the key elements of the conflict resolution process, such as the involved design parties and corresponding conflict resolution's options are identified and organized in a model. During CA, that model is used to analyze the different moves that the involved design parties can make during the conflict resolution process and to identify the conditions needed to solve the conflict situation.

Three different complexity levels of the conflict situations are modelled. The lowest level of complexity takes place when CM and CA result in a set of common conflict resolution proposals. In that case, conflict resolution can be achieved through CM and CA itself. The middle level of complexity takes place when CM and CA result in a set of mutually exclusive conflict resolution proposals. In that case, conflict resolution can be achieved through CC. The highest level of complexity takes place when CM and CA result in no conflict resolution proposal at all. In that case, resolution of the conflict situation can be achieved through CR.

In CC, it is assumed that the involved design parties individually provide an arbitrator with a set of mutually exclusive conflict resolution proposals to evaluate. Using that information plus knowledge available in its conflict-resolution casebase, the arbitrator evaluates the presented set of mutually exclusive conflict resolution proposals and determines the conflict resolution proposal to implement. As discussed, CR takes place when CM and CA do not provide the necessary conditions to achieve conflict resolution. Under that circumstance, computer-aided design (CAE) tools (e.g. dependency analysis) can be used to achieve conflict resolution.

Table 3 compares the method for conflict resolution reported in this article with relevant other research.

As indicated in table 3, the FDL-CR method follows and combines the advantageous features of previous computer-supported conflict resolution methods, but for the specific needs of resolving facility design conflicts. The FDL-CR method does not apply at present the capture of design rationale (e.g. Klein 1995), instead, it can rely on knowledge-based inference from previous conflict resolution successes. In addition, FDL-CR is built along the five approaches (stages) of resolution.

3.3. *Impact of the FDL-CR method in the field*

The FDL-CR method provides the basis for integrated detection and resolution of conflict situations in collaborative facility design. By incorporating the method on the Facility Description Language (Witzerman and Nof 1995), a computer platform for collaborative facility design, two highly related design tasks are integrated. The expected benefits of this integration of design tasks are reduced time for facility design and improved facility design quality. Because of the magnitude of the financial resources required for design, construction and operation of industrial facilities, the benefits of the integration of conflict detection and resolution in collaborative facility design cannot be overlooked.

To provide computer support for collaborative facility design, development of the FDL-CR method was imperative since important drawbacks and limitations associated with the existing conflict resolution methods for collaborative engineering design were recognized. The most impacting are the following.

- CM and CA are absent in existing methods that facilitate computer-supported conflict resolution in collaborative engineering design. CM and CA provide information that can be used for an early and therefore cost-effective resolution of the conflict situation. CM and CA are included in the FDL-CR method.
- Existing methods overlook the knowledge available in social sciences that is used in the resolution of human disputes of varying magnitude. Proven social sciences conflict resolution approaches were incorporated in the FDL-CR method.
- Existing methods rely mostly on human intervention to solve conflict situations of high complexity level, such as the case of competing conflict resolution proposals and no compromise solution allowed. Through computer-based learning, human-free conflict resolution can be developed to solve that type of conflict situations. Computer-based learning capabilities were incorporated in the FDL-CR method to facilitate the evaluation of mutually exclusive conflict resolution proposals without human assistance.
- A concept absent in existing methods is multi-stage (i.e. multi-approach) conflict resolution. Implementation of this concept helps to keep track of the cost of the conflict resolution process and to systematically address the conflict situation following a logic that has proved to be cost-effective solving human disputes at different levels (organizational, group, and, individual). The structure of the FDL-CR method is based on this concept.
- Existing methods lack mechanisms to record the result of conflict resolution process for further use when solving new conflict situations. Recording and using the results (successes and failures) of conflict resolution experiences

Method reference	Underlying design concepts	Difference/similarity with FDL-CR
Klein (1989, 1991, 1993, 1995)	Conflict resolution in general collaborative design	Investigation and development of a method for conflict resolution in collaborative facility design
	Use of hierarchies of conflicts and conflict resolution proposals, and a mechanism that maps a given conflict onto the corresponding conflict resolution proposal	Similar concept is used in FDL-CR
	Capture of design rationale	Not used in the current version
	Conflict resolution is an exception handling component of design services	Provides integrated conflict detection and resolution
Sycara (1993)	Resolution of labor-management conflicts	Conflict resolution in collaborative facility design
	System of specialized computer-based agents	Similar concept is used in FDL-CR
	Conflict resolution approaches: negotiation through a third party and persuasion	Conflict resolution approaches: negotiation, third party mediation, incorporation of additional parties, persuasion, and arbitration
	Fixed sequence of conflict resolution execution approaches	Similar concept is used in FDL-CR
Wong (1997)	Resolution of conflict situations in knowledge-based cooperative system	Conflict resolution in collaborative facility design
	System of specialized computer-based agents	Similar concept is used in FDL-CR
	Conflict resolution approaches: inquiry, arbitration, persuasion, and accommodation	Conflict resolution approaches: negotiation, third party mediation, incorporation of additional parties, persuasion, and arbitration
	Non-fixed sequence of conflict resolution execution approaches	Fixed sequence of conflict resolution execution approaches
Xie *et al.* (1998)	Resolution of inter-functional conflict situations	Conflict resolution in collaborative facility design
	Consideration of different complexity levels of conflicts	Similar concept is in FDL-CR
	Conflict resolution approaches: avoidance, accommodation, competition, collaboration, compromise, and hierarchical resolution	Conflict resolution approaches: negotiation, third party mediation, incorporation of additional parties, persuasion, and arbitration
	Fixed sequence of conflict resolution execution approaches	Similar concept is used in FDL-CR

Table 3. Comparison of the FDL-CR method for conflict resolution with other developments.

should improve the design process over time. In the FDL-CR method, the casebases of the participating design parties are updated to expedite future conflict resolution.

3.4. *Design and implementation details of FDL-CR*

FDL-CR, the development presented here, is the result of incorporating in FDL the conflict resolution capabilities supported by the introduced method for conflict resolution. To develop FDL-CR, the FDL's user interface has been modified to add the conflict resolution function to the FDL's functions menu. The FDL-CR's operation logic is as follows. Upon the detection of a conflict situation when evaluating a facility model with FDL, FDL-CR is instantiated to start the conflict resolution process in order to determine the conflict resolution proposal to implement. Once the conflict resolution process is complete and assuming that a conflict resolution proposal is available, the corresponding FDL model is updated by incorporating the changes associated with the proposal. Next, the updated FDL model is evaluated. If no new conflict situation is detected, then conflict resolution has been achieved, otherwise the conflict resolution process is repeated.

The FDL-CR's user interface works as follows. Whenever a conflict situation is detected, the conflict resolution process is instantiated by clicking on the FDL-CR button located at the bottom of the FDL's functions menu. Depending on the type of conflict that has been detected, FDL-CR displays windows with guidelines to be used to proceed with the conflict resolution process. Figure 2 shows the operation logic of the FDL-CR's user interface. As shown, the current implementation of FDL-CR assumes that the conflict-resolution process has proceeded without success through the first four stages of the introduced method for conflict resolution, and has reached the arbitration stage, which is the most complex one.

As shown in figure 2, FDL-CR has been developed to solve four types of conflict situations.

C(d): conflict situation in facility layout design.
C(f): conflict situation in the determination of the product routing.
C(r): conflict situation in the selection and programming of robotics equipment.
C(v): conflict situation in the selection of visual sensors and setting of operating parameters.

According to figure 2, once the conflict situation is identified, CM and CA are executed following the Graph Model for Conflict Resolution software, GMCR, developed by Fang *et al.* (1993). If CM and CA result in X (a set of common conflict resolution proposals), then the FDL design model is modified according to the changes associated with the common conflict resolution proposal in order to determine if new conflict situations would emerge from the revised implementation. If CM and CA result in Y (a set of mutually exclusive conflict resolution proposals), then a neural-fuzzy inference system (discussed in Section 3.5) is run to execute the CC phase of the arbitration stage. If CM and CA result in Z (no conflict resolution proposal), then CAE tools (e.g. dependency analysis, product flow analysis) are applied to execute the CR phase of the arbitration stage. As in the case in which CM and CA result in X, whenever CM and CA result in Y or Z, the FDL design model is revised according to the changes associated with the recommended conflict resolution proposal to determine if new conflict situations may emerge again. If no new conflict situation is detected, then it can be considered that conflict resolution

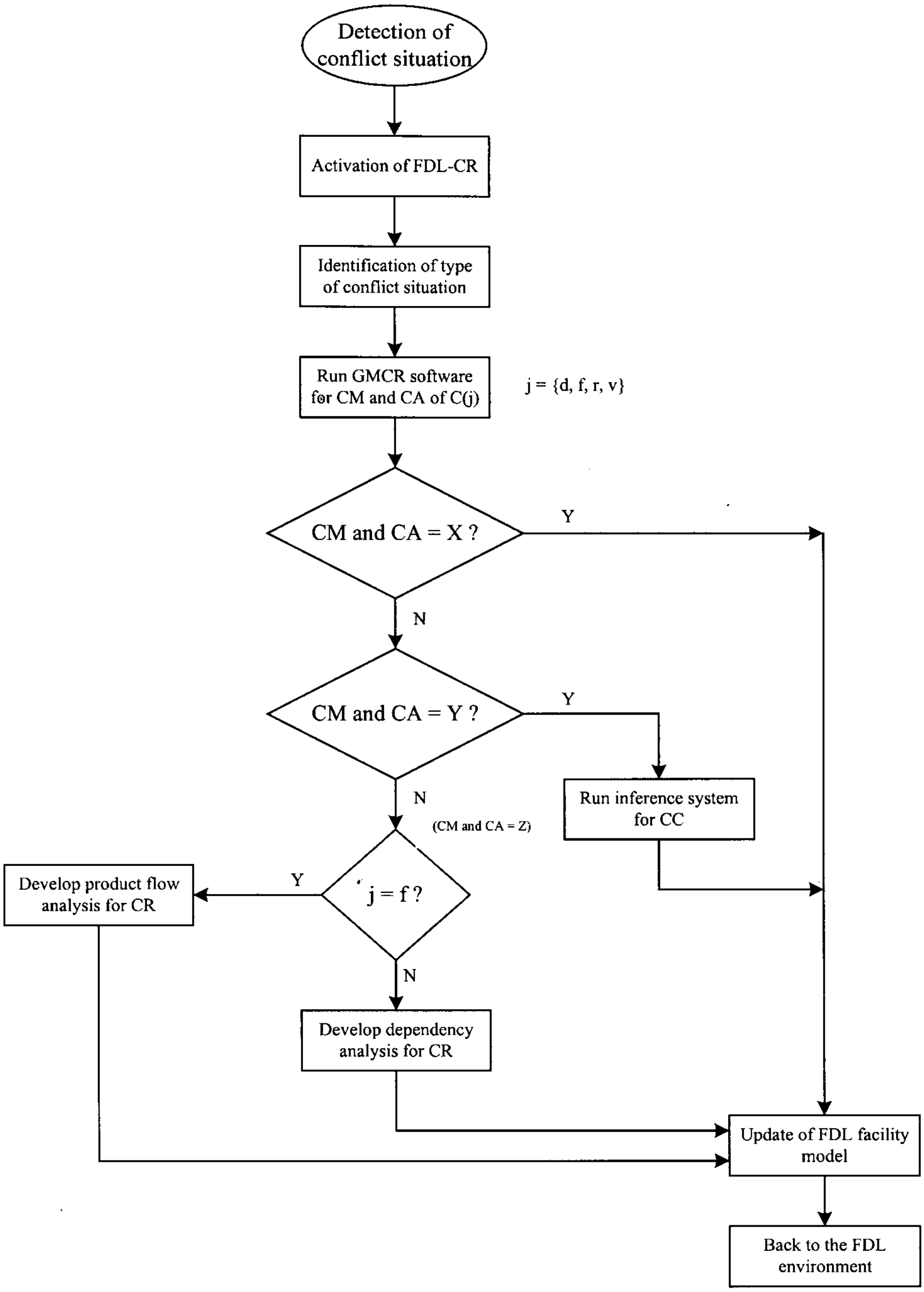

Figure 2. Operation logic of FDL-CR.

has been achieved, otherwise FDL-CR can be re-instantiated to repeat the conflict resolution process.

According to the experimental results obtained by Xie *et al.* (1998) in their study of the impact of the complexity level of conflicts on the resolution of interfunctional conflict situations, a competition approach for conflict resolution should be applied to solve conflict situations of high complexity level, whereas a collaboration approach should be applied to solve conflict situations of low complexity level. These results were considered in the design of the new FDL-CR method for the confrontation of conflicting parties phase.

To illustrate the resolution of conflict situations by a competition approach and to explain the operation of FDL-CR, FDL-CR is applied to solve a conflict situation where CM and CA result in a set of mutually exclusive conflict resolution proposals. For such a case, the CC phase of the arbitration stage is developed.

To evaluate the usefulness of the FDL-CR method in the CC phase of the arbitration stage, the following definition is necessary.

Definition: Let $\lambda_1, \lambda_2, \ldots, \lambda_n$, be a set of mutually exclusive conflict resolution proposals, where λ_i is proposed by the conflicting design party i, and let λ^* be the conflict-resolution proposal recommended for implementation. Also, let U be a binary indicator of the usefulness of the method that supports conflict resolution when solving a particular conflict situation through confrontation of conflicting design parties. Then,

$$\mathrm{U} = \begin{cases} 1, & \text{if } \exists\, \lambda_i \ni \lambda = \lambda^* \\ 0, & \text{otherwise.} \end{cases}$$

This definition implies that if one of the mutually exclusive conflict resolution proposals being evaluated solves the conflict situation in question, then that conflict resolution proposal should be recommended for implementation.

3.5. *Development of a neural-fuzzy inference system to support conflict resolution*

To implement conflict resolution through confrontation of conflicting design parties, several alternatives were considered. The most advantageous turned out to be a neural-fuzzy system. The advantages of a neural-fuzzy approach are the following.

- Effective evaluation of mutually exclusive conflict resolution proposals.
- Capability to implement computer-based learning.
- Accuracy when verifying the effectiveness of the method for conflict resolution.
- Simple to implement and explain/illustrate the concept of conflict resolution through confrontation of conflicting design parties.

MATLAB® is the software used as platform to develop the neural-fuzzy system. ANFIS (Adaptive Neural Fuzzy Inference System) (Jang 1993), one of the MATLAB's® tool boxes, provides the means to build neural-fuzzy systems for decision-making and computer-based learning.

The neural-fuzzy inference system in question was built entirely through the training process of ANFIS. This training process included the computation of the system parameters (e.g. mean and variance of the inputs membership functions), determination of if–then rules, and definition of system settings such as aggregation, implication and defuzzification methods. In the development it was assumed that the inputs have each three membership functions (e.g. low, medium, high). Domain knowledge was required to define parameters such as the number and shape of the membership functions of the input variables. The components of the developed inference system are four inputs, a set of 81 if–then rules and one output.

Parameter	Time to replace the visual sensor	Time to relocate the pick-up station	Cost of replacing the visual sensor	Cost of relocating the pick-up station
Mean	4.75	5.50	11.50	10.0
Variance	1.0	0.75	1.75	2.0

All times are in minutes and costs in dollars.

Table 4. Normal probability distributions of data used to train the developed learning module.

Parameter	Time to replace the visual sensor	Time to relocate the pick-up station	Cost of replacing the visual sensor	Cost of relocating the pick-up station
Mean	4.75	5.50	11.50	10.0
Variance	1.50	1.125	2.625	3.0

All times are in minutes and costs in dollars.

Table 5. Normal probability distributions of data used to evaluate conflict resolution proposal.

To achieve the desired behaviour of the learning system, data in the form of input–output sets were used. A text file was generated to provide data to train ANFIS. Each row in the training text file constituted one training rule. The file was comprised of five columns, four columns for the inference system's inputs and one for the desired corresponding output. The input data were randomly generated. Table 4 shows the parameters of the normal probability distribution used to generate the training data. The parameters were defined using domain knowledge. Thirty-five training rules were defined (as explained above) and used for training. One hundred and thirty training epochs resulted in a training error approximated to 0.0.

Randomly generated data were used to evaluate sets of the inference system's inputs in order to determine the conflict resolution proposal to implement. Table 5 shows the parameters of the normal probability distribution used to generate data for that purpose. Such parameters were defined using domain knowledge.

After evaluating a set of inputs, the inference system returns a fuzzy value. This value was defuzzified using another neural-fuzzy inference system in order to obtain a crisp value from the inference system's output.

4. Implementation of the CC phase of the arbitration stage

To develop the concept of conflict resolution through confrontation of conflicting design parties proposed here, the four typical conflict situations (i.e. C(v), C(d), C(r), C(f)) were analysed (Lara 1999). Each conflict situation was analysed in a case study. The case study for the conflict situation C(v) is described here. In the preparation of the presented case study, the following guidelines were assumed.

- A conflict situation emerged from the collaboration between an industrial engineering design party (IE) and an electrical engineering design party (EE), who teamed up to plan visual sensing devices needed for a robotic facility.
- The discrepancies in design preferences between the IE and EE were revealed when the model of the robotic facility under design was analysed with FDL. Figure 3 shows a snapshot where the FDL's field-of-view evaluation function reports the conflict situation. In the facility shown, a visual sensor is used for part detection in an assembly station and in a pick-up station. According to figure 3, FDL reported that the sensor's field of view for the pick-up location was out of range by 1017.67 mm. If not corrected, this design deficiency may disturb the manufacturing operations and may result in wasted operation time.
- The process to solve this conflict situation has proceeded without success through the first four stages of the conflict resolution process outlined in figure 1.
- In the fifth stage of the conflict resolution process, the IE and EE provide an arbitrator (AR) with time and cost estimates of two mutually exclusive conflict resolution proposals: replacement of the visual sensor (IE) and relocation of the pickup station (EE). AR settles the conflict after evaluating the conflict resolution proposals proposed by the involved design parties.

In the development of the case study, it was also assumed that the role of AR is performed by a neural-fuzzy inference system, the information provided by the IE

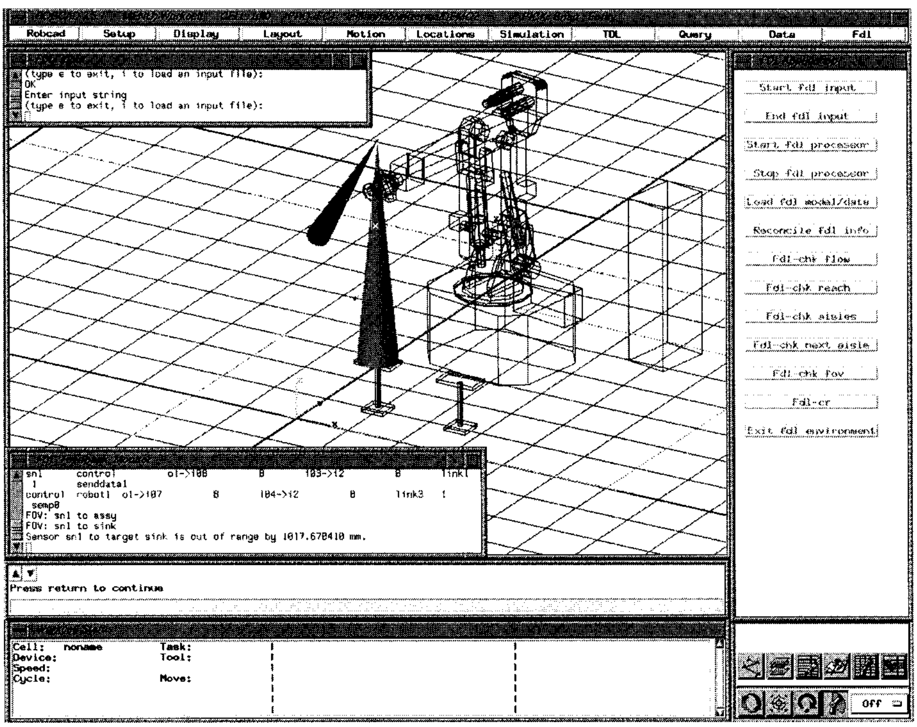

Figure 3. Detection of a conflict situation using the FDL's design evaluation functions.

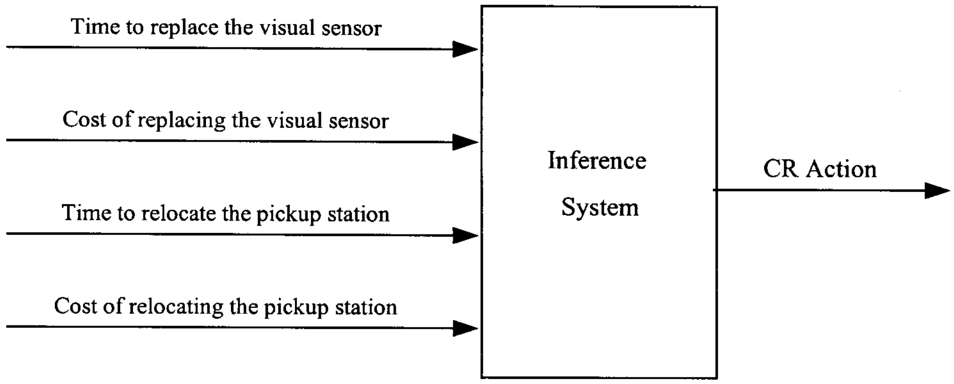

Figure 4. Inference system developed to model the CC phase of the arbitration stage.

and EE is modelled as the system's inputs, the AR's rationale is modeled by a set of if–then rules, and the AR's final decision is represented as the system's output.

As shown in figure 4, the inference system's inputs provided by the EE are time to replace the visual sensor and cost to replace the visual sensor, whereas those provided by the IE are time to relocate the pickup station and cost to relocate the pickup station.

Table 6 shows a sample of the experimental results obtained during the evaluation of the aforementioned mutually exclusive conflict resolution proposals with the developed inference system. Columns 2–5 in table 6 show input sets containing times

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Case	Time to replace the visual sensor	Time to relocate the pick-up station	Cost to replace the visual sensor	Cost to relocate the pick-up station	ANFIS' conflict resolution action	Domain knowledge-based conflict resolution action	U*
1	**4.80**	**4.45**	**10.19**	**10.25**	**2**	**2**	1
2	7.18	4.43	12.88	7.75	2	2	1
3	4.73	4.20	7.87	9.16	2	2	1
4	**5.83**	**5.92**	**13.40**	**12.30**	**1**	**1**	**1**
5	6.13	4.34	12.33	8.56	2	2	1
6	4.16	7.06	11.62	9.25	1	1	1
7	5.15	6.38	15.41	13.37	1	1	1
8	4.33	5.08	9.30	12.81	1	1	1
9	**4.43**	**5.39**	**16.87**	**6.57**	**2**	**2**	**1**
10	3.55	7.45	13.16	9.31	1	1	1
11	**5.90**	**6.28**	**16.01**	**4.24**	**1**	**1**	**1**
12	4.04	6.28	9.67	10.67	1	1	1
13	5.01	4.75	11.47	7.85	2	2	1
14	4.66	5.23	14.49	9.45	1	1	1
15	4.20	5.16	6.98	7.03	1	1	1

U*, usefulness parameter of the FDL-CR method.
All times are in minutes and costs in dollars.

Table 6. Sample of experimental results of the evaluation of conflict resolution proposals.

to replace the visual sensor, times to relocate the pick-up station, the costs of replacing the visual sensor and the costs of relocating the pick-up station, respectively. The sixth column in table 6 is the conflict resolution recommendation provided by the developed inference system for each of the given input sets. The seventh column, for comparison, is the conflict resolution recommendation that would be obtained using human reasoning and domain knowledge. This knowledge is provided by human experts in the field who using their intuition and expertise make subjective judgements on how the conflict situation being addressed can be solved. As for the data in the sixth and seventh columns in table 6, the value 1 means 'relocation of the pick-up station', whereas 2 means 'replacement of the visual sensor'. Column 8 in table 6 shows the resulting usefulness index.

As shown, the conflict resolution recommendations provided by the developed inference system always matched those obtained through human reasoning with the same domain knowledge. Consequently, the method's usefulness is always 1.

The results achieved in the presented case study are consistent with those obtained in the other three case studies in terms of the usefulness criteria introduced here.

5. Discussion and conclusion

Several aspects of the FDL-CR's conflict resolution capabilities merit further discussion. They include the design and effectiveness of the new method, and its impact on the field of computer-supported collaborative facility design.

The developments introduced in this research include the following items.

- FDL-CR: a computer tool that allows integrated conflict detection and resolution for collaborative facility designers.
- Systematic method for resolution of conflict situations in collaborative design. This method combines several resolution approaches (direct negotiation, third party mediation, incorporation of additional parties, persuasion and arbitration) which are applied to prevent perpetuation and escalation of conflict situations. The resolution is accomplished by structuring the arbitration approach to allow for objective conflict modelling and analysis, confrontation of conflicting parties and mechanisms to enforce conflict resolution.
- Neural-fuzzy inference system (including quantitative and qualitative information and knowledge) to facilitate the resolution of conflict situations through the confrontation of conflicting design parties. It constitutes the CC phase of the arbitration stage in the new method.
- Means for automatic conflict resolution, which was accomplished by the development of the neural–fuzzy inference system.

FDL-CR's usefulness was validated through a series of design case studies, of which one is described here in detail. The new method supported the resolution of these conflict situations that are typical in collaborative facility design. The detailed case study discussed here involved the selection of visual sensors and the setting of their operating parameters. The other cases are documented in the references by the authors.

In the development of FDL-CR, in addition to the general method, two essential areas are the computer-based experiential learning, and the CAE role in measuring, analysing and evaluating alternative proposals for conflict resolution.

The structure of the developed inference system resulted from evaluation of several alternatives of membership functions. The preferred structure was determined based on two criteria: how well the inference system models the confrontation of conflicting design parties, who provide an arbitrator with information on the implementation of the proposed alternatives, and the arbitrator's decision process to rule on the recommended resolutions. The experimental results (table 6) show that the answers provided by the developed ANFIS matched conflict resolution recommendations obtained from human reasoning with the same domain knowledge. It therefore indicated that the FDL-CR method for conflict resolution is effective.

Input–output mapping and domain knowledge were used to define a set of if–then rules to train the developed learning modules. Indeed, conflict resolution recommendations provided by the analysis are highly dependent on the sources of domain knowledge used for training. Based on the Central Limit Theorem, it was assumed that the normal probability distribution was a good approximation for the probability distributions of the training data. The parameters specified for the normal probability distributions were also based on the domain knowledge.

Cases 1, 4, 9 and 11, which are highlighted in table 6, prove the effectiveness of the FDL-CR method to settle complex conflict situations. Cases 1 and 4 involve the evaluation of conflict resolution proposals with approximately similar implementation time and cost. Cases 9 and 11 illustrate that the conflict resolution proposal with the smallest implementation time can have an implementation cost considerably greater than that of the conflict resolution alternative requiring the longest implementation time. In such cases (1, 4, 9 and 11 in table 6), deciding the conflict resolution proposal to recommend required the use of political considerations, a form of subjective and qualitative reasoning that was included in the ANFIS training. This form of subjective reasoning facilitates the resolution of two extreme conflict situations. In one of them, the relative implementation times and costs of the involved conflict resolution proposals are approximated. In the other, the conflict resolution proposal with the smallest implementation time happens to have an implementation cost much greater than that of the conflict resolution proposal with the longest implementation time. In both cases, due to its complex nature, the resolution of the conflict situation is based on a subjective prioritization of implementation times and costs. This subjective prioritization of implementation times and costs is modelled in the FDL-CR method as a set of political (social) considerations, which, in turn, have been incorporated in the ANFIS' inference mechanism to settle conflict situations consistently. The achieved experimental results presented in table 6 prove the usefulness of the method.

As shown in figure 5, integrated conflict detection and resolution, which represents an integral support to collaborative facility design, has resulted from incorporating in FDL conflict resolution capabilities provided by the new conflict resolution method. Integrated detection and resolution of conflict situations in collaborative facility design reduces the development time and increases the quality of facility designs.

Possible avenues to extend this research are as follows.

- Investigate a multi-agent system to model and emulate the conflict resolution process.
- Investigate the effects and resolution of interrelated conflict situations in collaborative facility design itself.
- Investigate a multi-agent system to model and emulate the collaborative facility design process.

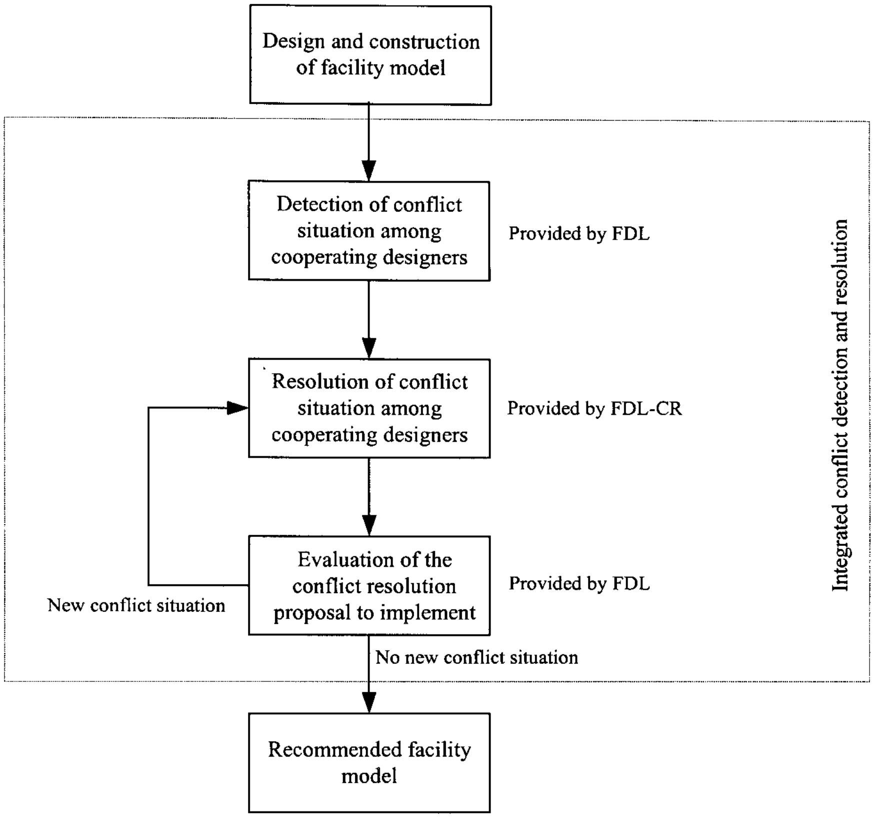

Figure 5. Integration of conflict detection and resolution in collaborative facility design.

- Increase the range and complexity of conflict situations in collaborative facility design that can be resolved with FDL-CR.

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Appendix 1: Nomenclature

Acronyms

AR	arbitration party,
ANFIS	adaptive neural-fuzzy inference system,
CA	analysis of conflict situations,
CC	confrontation of conflicting parties,
CM	modelling of conflict situations,
CR	resolution of conflict situations,
C_{PE}	conflict perpetuation and escalation,

EE	electrical engineering design party,
GMCR	graph model for conflict resolution,
IE	industrial engineering design party,
MAS	multi-agent system.

Symbols

C(d)	conflict situation in facility layout design,
C(f)	conflict situation in the determination of product routing,
C(r)	conflict situation in the selection and programming of robotics equipment,
C(v)	conflict situation in the selection of visual sensors and setting of their operating parameters,
U	usefulness parameter of the method that provides capabilities for resolution of conflict situations in FDL-CR,
X	set of common conflict resolution proposals (λ) after conflict modelling and analysis (CM and CA),
Y	set of mutually exclusive conflict resolution proposals (λ) after conflict modelling and analysis (CM and CA),
Z	no conflict resolution proposal (λ) after conflict modelling and analysis (CM and CA),
α	design party that brings about the conflict situation,
β	α's opposing parties,
δ	mediation party,
δ	specialized parties,
λ	conflict resolution proposal,
λ	plural of λ,
λ_i	conflict resolution proposal proposed by *i*-th party,
λ^*	conflict resolution proposal recommended for implementation,
$\tau(\lambda_i)$	counteroffer to the conflict resolution proposal suggested by the *i*-th party.

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