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Collaborative Product Development in CAD and CAPP

An approach based on communication due to constraint conflicts and user initiative

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Abstract

This paper addresses collaborative product development, focusing on computer support of collaboration between users of CAD systems alone, between users of CAPP systems alone and between users of both CAD and CAPP systems. Computer support of collaborative product development may enhance informal information exchange. Apart from formal information exchange between CAD and CAPP systems, informal information exchange is necessary in achieving the goals of Concurrent Engineering. Collaboration can be started in a number of ways; as a result of one or more conflicts in constraints belonging to several users or voluntarily on the initiative of a user. Both these ways of starting collaboration should be supported. A prototype implementation restricted to a re–design support oriented CAD system supporting both conflict based and voluntary communication is presented. The re–design support system currently supports several constraint types. The present implementation uses parameter constraints in the support of conflict based communication. A parameter constraint solver based on the use of simulated annealing is employed.

Keywords

CAD, CAPP, collaborative design, concurrent engineering, constraints, features, multi–user systems

1 INTRODUCTION

Due to the growing interest in concurrent engineering as a research topic, a clear trend towards the development of computer support of collaborative product development can be observed.

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This paper restricts itself to computer support of collaborative product development in the fields of CAD and CAPP. There are several reasons for considering this area. Bridging island automation is one reason as today's CAD and CAPP systems often still are isolated, thus restricting their users not only in the exchange of formal product model data but also in communicating informally via the system. In the philosophy of Concurrent Engineering, a team approach is essential, so that designers and process planners and other team members should cooperate more. However, not all members of a project team work at the same site or time, which means that close cooperation is difficult. Moreover, due to the fact that design is often performed at one company or department, while process planning is performed at another, computer support of collaborative product development in CAD and CAPP is required in order to make geographically different sites virtually more the same.

It is our philosophy that design and process planning will remain separate disciplines, although a tendency can be observed of merging the two into one. Both specializations are so complex and require so much knowledge and so many skills that it does not seem useful to give all process planning tasks to designers (or vice versa). Of course designers will have a general awareness of manufacturing and process planners of design, but it seems impossible to have complete insight into the other discipline at all levels of detail. In contrast, in Next–Cut, a concurrent design system which aims at integrating detailed component design and CNC process planning, a user is responsible for both design and process planning (Cutkosky et al. 1992). However, this is a situation that should be avoided. Of course, due to a high level of automation in CAPP systems, process planners will have a different task compared to the previous situation. Assuming that they will have more time available in case CAPP systems are employed, they have more time to advise designers with regard to manufacturing issues. To have both process planners and designers perform design as well as make process plans, seems a bit unrealistic.

Cooperation may be formal or informal in two ways. The first way is that there is both formal and informal information exchange between systems. An example may be the relationship between a contractor (design) and a subcontractor (process planning), where a physical separation between process planners and designers exists. The formal information exchange can be the exchange of a product model in some standardized format. The informal information exchange between systems may be the communication between the users of the systems. The second way of formal/informal cooperation is that communication between users (which is an informal part of the information exchange between systems) can be divided in constraint–based (formal) communication and voluntary (informal) communication. Our aim is to come to both a formal and an informal integration of design and process planning for each discipline individually and between the two disciplines considered.

Collaborative product development is part of concurrent engineering. There are many definitions of concurrent engineering. The following definition is the most practical for our research, as it gives a clear objective: Achieving maximum cooperativeness with a minimum of communication by maximizing the transparency. Transparency itself can be defined as the clarity of processes through which people can see the consequences of their decisions. In the case that clarity is provided, it is likely that people will have a global view of the consequences of these decisions. However, this definition of concurrent engineering does not provide a means to measure its performance or effectiveness. Effectiveness of concurrent engineering can be measured by how long it takes to find and correct a design mistake (Sevenler et al. 1993).

In collaborative product development coordination and integration problems may occur. Crabtree et al. have identified six broad categories of coordination and integration problems in their analysis of coordination problems (Crabtree et al. 1993):

- The information acquisition problem which relates to unavailability of information, mostly design rationale, due to difficulties in acquiring it.
- The information access problem which can be seen as the difficulty of accessing information that is either physically or electronically available.
- The knowledge access problem occurs when expertise of senior people, needed by less experienced designers, is unaccessible due to the fact that the high demand for advise from these senior people makes them hard to contact.
- The decision interdependence problem which relates to how individual decisions can cause severe coordination problems and introduce delay to the program.
- The activity management problem which relates to the non–adherence to schedules for non–technical reasons.
- The agent access problem which arises when key decision makers are unavailable when an important decision is to be made.

The coordination problems may influence each other, but the decision interdependence problem is often quoted as probably the largest and most important problem. As for decision interdependence Crabtree et al. (1993) write: "..decision interdependence requires a method of modelling and managing the inter–dependencies. Luckily there appears to be a solution: constraint networks."

A unified way to represent different levels of objects and the constraints between them, as described in e.g. (Shah et al. 1993, 1994) and (Salomons et al. 1994b, 1995a), together with a unified constraint satisfaction method seems to be an interesting and powerful approach to combine with the ideas by Crabtree et al. (1993). This approach has been partly implemented in a collaborative product development module for FROOM, a CAD prototype which applies constraints. This paper discusses the general philosophy and the current implementation. At present, no CAPP system has been involved in the implementation effort, although it was considered in the overall philosophy and design. However, the concepts of applying constraints and communication in process planning are similar to design. Therefore, once proven to work within design, the concept will allow to be taken over into CAPP. The CAPP systems that have our special interest are the PART (van Houten 1991) and PART–S (de Vin et al. 1993) systems as these were (respectively are) in–house developments. Formal integration between FROOM and PART–S has previously been considered in (de Vries et al. 1994). In this approach the focus was not on communication between designers and process planners but on a design by least commitment approach in which the role of abstract features and DFM rules was investigated.

By the usage of constraints, responsibilities will not only be shared or negotiated but also clearly appointed to a group member. Application of constraint satisfaction will provide rapid feedback. This will lessen the communication needed and improve the clarity of the design process. In the following, the FROOM system is addressed in section 1.1. and the constraints used in FROOM are addressed in section 1.2. Finally, section 1.3 will provide an overview of the remainder of this paper.

1.1 FROOM

FROOM stands for Features and Relations used in Object Oriented Modelling. FROOM is a prototype of a feature based re–design support system allowing the modelling of both components and assemblies. Relations can be expressed between the different objects by means of constraints. The focus has been on the support of re–design tasks because in practice a high percentage of all mechanical engineering design tasks can be considered as re–design tasks.

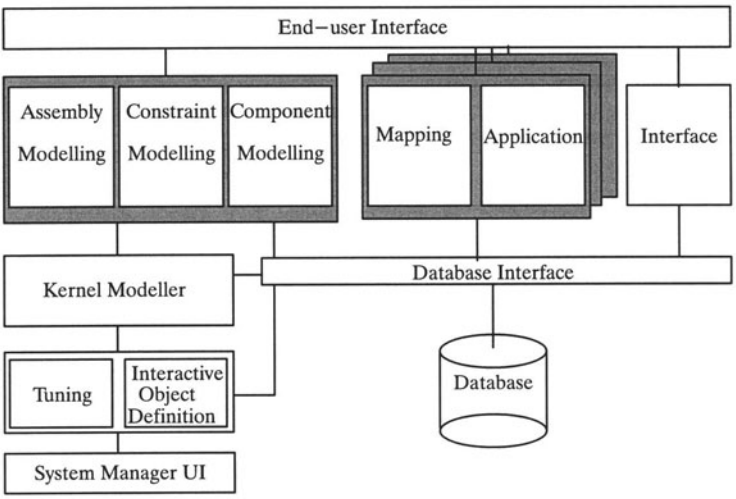

Figure 1 System architecture of the FROOM system.

The system architecture is divided into several functional modules, shown in figure 1. The modules exchange information through the database. Two different types of users are discerned: end–users and system manager users. The end–users are the designers who do the actual (re)design work. They design assemblies, components etc.. One of the philosophies that has driven the development of FROOM is that both system users and end–users should perform as little programming as possible. The system manager user customizes the system to an application domain, to a certain company as well as to certain users. A system manager user may be a project manager as well. For more details on FROOM refer to (Salomons, Kappert et al. 1993) for its concepts and to (Salomons, van Slooten et al. 1993) for its methodic design. More recent references can be found in (Salomons et al.1995a,b,c,d).

A typical task for which the system manager user interface can be used is Interactive Object Definition. Objects can be divided into four categories: assemblies, components, features and the basic feature–elements. Interactive object definition can be divided into three sub modules: the Interactive Assembly Definition Module, the Interactive Component Definition Module, and the Interactive Feature Definition Module. The Interactive Feature Definition Module has been described in (Salomons et al. 1994a) and (Geelink et al. 1995). Other responsibilities of the system manager user are for instance the definition of domain dependent knowledge such as catalogues, standards etc..

The FROOM end–user interface, shown in figure 2, consists of two main parts: a graphic–interactive window for directly manipulating geometry similar to those in commercial CAD systems and a (context) window in which a network of objects and relations at various levels of abstraction, is displayed. This network represents the product model and has a bi–directional association with the geometry window. The network is a conceptual graph (Sowa 1984). It is not only used for presentation purposes, but also for the internal representation of objects and their relations and is discussed extensively in (Salomons et al. 1994b). The objects and relations can be detailed further to a lower level of abstraction. The graphic interactive window supports bottom–up design tasks while the context window supports top–down design tasks, thus allowing

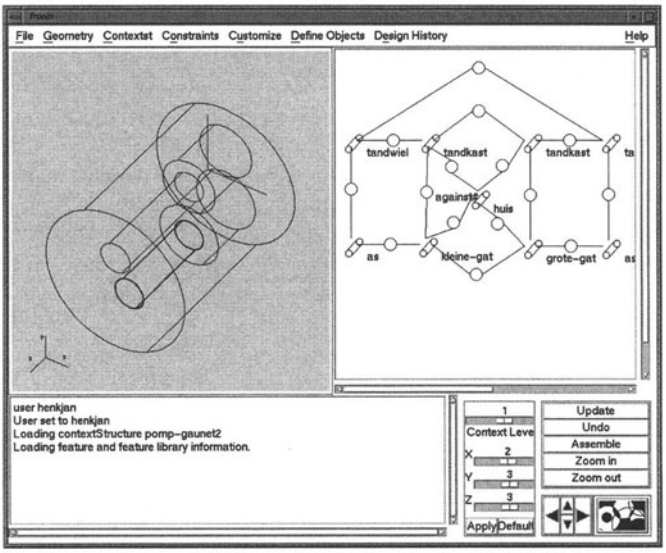

Figure 2 The FROOM user interface, consisting of a geometry window and graph (context) window that have a bi–directional association.

a mixed top–down and bottom–up approach. A design history function is also available in FROOM as well as a functional tolerancing functionality (Salomons et al. 1995a,b,d).

1.2 Constraints in FROOM

There are various definitions of constraints. The following definition is used within the FROOM context: *A constraint is either imposed on a single object or represents a desired relationship among two or more objects.* The constraint classification within FROOM discerns five types of constraints:

- Assembly constraints: these constraints are defined between (faces of) components to enable the modelling of an assembly. In FROOM, the assembly constraints are symbolic constraints like "against", "align/fit", "contact", "orient", and "parallel offset".
- Feature internal geometric constraints: these are (non variational) constraints within a feature, between the elements that constitute the feature; faces, edges etc.. Feature internal constraints currently applied in FROOM are for example: parallel, perpendicular, adjacent and co–axial.
- Feature external geometric constraints: these are (non variational) constraints between feature elements and non–feature elements within a component. These feature types are similar to the feature internal constraints: parallel, perpendicular, adjacent, etc.. These constraints are important for defining how features are to be instantiated and with respect to their behavior.
- Variational geometric constraints: these constraints can be considered as tolerance constraints and they can be defined between faces, between features or inside features or

even on a single surface. However, tolerances are related to functions and thus, the assembly model is important as well.

- Parameter constraints: these constraints can be defined either by the system manager or the end–user in FROOM. They can be regarded as algebraic equations and affect dimensions, geometry, forces, stresses etc..

The first three types of constraints are related to nominal geometry. A technique for solving geometric constraints called Degrees of Freedom Analysis, as proposed by Kramer (Kramer 1992) has been adopted for solving these constraints. Conventional geometry constraints solving packages use iterative numerical techniques like for instance Newton–Rhapson. Kramer, however, works from the geometry directly instead of using numerical techniques. Therefore, DOF analysis is a novel, more intuitive technique for solving geometric constraint problems and shows to be superior to conventional, iterative numeric techniques. The technique relies on a layered approach to solving a constraint problem. The first step is to reason symbolically about how to assemble a collection of "ghost" parts. The next step is to use the resulting assembly plan to guide the solution of the equations resulting from an algebraic description of the constraint problem. This assembly plan guides the solution of the equations, by implementing actions as simple equations which are solved in stylistic ways (Kramer 1992).

In FROOM, Kramer's DOF analysis approach has been translated from the original kinematics domain into solving geometry related constraints on assembly, component, feature and feature element level. For assemblies, the approach by Liu and Nnaji (1991) was combined with Kramer's approach. The general application of the DOF analysis approach in FROOM is detailed in (Salomons et al. 1994b) and (Salomons 1995a). In feature definition DOF analysis is combined with similar ideas for a 2D sketcher by Arbab and Wang (1989); more details are provided in (Salomons et al. 1994a, 1995a). Similar research on the use of DOF analysis in assembly and feature modelling has been reported in (Anantha et al. 1992) and (Shah et al. 1993, 1994).

The satisfaction of variational geometric constraints is based on the work by Clément et al. (1993, 1994). This work is based on the kinematics of small rotations and translations. For tolerance analysis, this theory has been combined with the kinematics theory by Kramer on large rotations and large translations. For more details refer to (Salomons et al. 1995a,b).

Parameter constraints in FROOM are solved using the simulated annealing approach by Thornton (Thornton 1993) and (Thornton & Johnson 1993). This parameter constraint satisfaction method will be explained further in section 4 as – for the moment – this is the only constraint satisfaction method in FROOM applied to collaborative product development. However, all the five constraint types mentioned earlier can be used as a basis for communication in a collaborative product development module.

1.3 Organization

The organization of the remainder of this paper is as follows. Section 2 briefly summarizes related literature. Section 3 describes the design of the module for collaborative product development in FROOM; collaborative modules for CAPP systems like PART will be similar to this module. Section 4 elaborates on the constraint satisfaction method used for solving parameter constraints that was applied in the collaborative design module as presented here. Section 5 addresses the present implementation of the collaborative product development module in FROOM. Finally, in section 6 conclusions and recommendations are presented.

2. RELATED LITERATURE

Roughly, one can divide multi–user systems into group collaboration architectures that do not use constraints as a basis for cooperation, and those that do use constraints as a basis for cooperation. The non–constraint based systems are addressed in section 2.1 while the constraint based ones are elaborated in section 2.2.

2.1 Multi–user systems without constraint–based communication

There are different multi–user systems that do not use constraints as a basis for cooperation. One such a multi–user system is PACT (Palo Alto Collaborative Testbed), a concurrent engineering structure that encompasses multiple sites, subsystems and disciplines (Cutkosky et al. 1993). PACT included Next–Cut (Cutkosky et al. 1992) as a subsystem and demonstrated how an agent–based approach could be applied to a multi–disciplinary design task. Four independently developed, existing multi–tool systems were encapsulated as agents. Agents are defined as computer programs that communicate with other external programs exclusively via a predefined protocol. These agents communicated through facilitators that translate tool–specific knowledge into and out of a standard knowledge–interchange language. In SHADE (SHAred Dependency Engineering), an extension of PACT, this language is called KIF (Olsen et al. 1994). Ontologies, defined as agreed upon sets of terms and meanings that enable parties to exchange knowledge for some purpose in some domain, are used to build such a language.

Drawbacks of PACT are its decentral and informal organization. As there is no (seemingly) central database, each agent has to know where it can find the information needed. Changes in (re)design can be made freely, without any responsibility or consideration towards the consequences for other users. In addition, ontologies were informally documented. This implies that a shared knowledge base does not exist within this testbed. Another multi–user system, related to PACT and SHADE, is SHARE (Toye et al. 1993). SHARE uses ontologies as well but these are centrally stored. Constraint solvers are present in SHARE but it is not clear if these are intended to start communication, and if so, how this actually works.

An integrated approach to design data has been made by Shah et al. (1992). Shah et al. created a design environment comprising a number of specialist design systems that cooperatively solve design problems, from conceptual lay–out to detailing.

During collaborative product development, both communication and social behavior play an important role. Multi–user communication systems will have to support social behavior. Studies of social behavior during collaborative product development (e.g. brainstorm sessions) performed by Tang have lead to the following recommendations for multi–user communication systems (Tang 1991):

- Convey gestures, maintaining their relationship to the drawing space
- Convey the process of creating and using drawings, with a minimal delay
- Provide concurrent access to the drawing space
- Allow intermixing among drawing space functions and actions
- Enable all participants to share a common view of the drawing space (WYSIWIS – What You See Is What I See)

One of the first experimental tele conferencing systems trying to apply these recommendations was TeamWorkStation, a desktop real–time shared workspace, developed by Ishii (Ishii 1990, 1991). Another distributed multi–party desktop conferencing system called MERMAID (Multimedia Environment for Remote Multiple Attendee Interactive Decision–making) is aimed to en-

able real–time conferences by interchanging information through video, voice and multimedia documents (Watabe 1990). Commercial tele conferencing software packages, containing a lot of the above mentioned required functionality, are already available, e.g. InPerson™ (Silicon Graphics 1994). However, InPerson™ lacks some of the required functionality; for instance project management and design history.

2.2 Multi–user systems with constraint–based communication

Wong et al. have developed a collaborative engineering system in which the representation of product information supports communication and coordination (Wong et al. 1993). This product information, encoded in an information model called SHARED, includes not only the geometric and physical properties of the product and its parts but also information about functions, constraints and the design rationale. Taleb–Bendiab et al. present a model of collaborative design embodied in a multi–agent system (SIMAD), using constraints as a basis for communication (Taleb–Bendiab et al. 1992). However, both references are not very clear on the nature and use of their constraint satisfaction methods.

Bowen et al. have shown that constraint–based systems can provide a good basis for collaboration and negotiation by the introduction of a constraint–based programming language, called Galileo3 (Bowen and Bahler 1992, 1993). Galileo3 is able to perform some constraint satisfaction as well as constraint monitoring on parameter constraints. Constraint monitoring, in the Galileo context, means accepting additional parameter and constraint declarations from the user and attempting to derive as many logical consequences of these declarations as possible. However, Galileo3 is unable to handle non–linear equations. The user–interface is very basic and adding and retracting constraints by designers requires programming skills. This is a severe drawback as designers are not programmers in the first place.

Another constraint–based multi–user system is ParMan, a collaborative design agent that is part of the SHADE project (Kuokka et al. 1994). It uses parameter constraint satisfaction based on CLP(R) (Jaffar et al. 1992) in order to support collaborative engineering. CLP(R) is a constraint programming language able to solve (in)equalities, linearities and (some) non–linearities, using different types of iterative numeric techniques. Although a programming language is used, no programming by the designer is required as a (powerful) constraint editor is applied. Apart from the underlying technologies, the user interface shows some similarity with the FROOM system. A drawback of ParMan is that each user has to explicitly make his constraints available to other users. This means that the interdependency problem cannot always be solved due to forgetting to make private constraints public. Therefore, a more fruitful approach can be that constraints are made publicly available by default, while users still would have the possibility to have private constraints but that the private constraints have to be explicitly selected instead of the other way around.

3. DESIGN OF A MODULE FOR COLLABORATIVE PRODUCT DEVELOPMENT IN FROOM

The methodic design approach by van den Kroonenberg (1985) has been applied to the design of the module for collaborative product development in FROOM. In fact, this methodology has been applied to the design of FROOM as a whole (Salomons, Kappert et al. 1993, Salomons, van Slooten et al. 1993). This approach provides a structured design approach, allows for discussing the design and helps in identifying weak points. The first aim is to come to a functional black

box description of the system with input and output characteristics. This is shown in figure 3. This figure can be explained as follows:

Before a collaborative design session starts, it is possible that some previously designed parts and/or assemblies, including design history, can be re–used. It is the task of the project leader (system manager) to divide the tasks on the basis of a functional, modular structure that he can pre–define. Subsequently he can assign parts of the total structure to individual team members or even teams who then have to work these parts out. The steering control comprises design knowledge of the team, design experience of the team and the manufacturing knowledge of the team. These controls of the process are necessary to come to a (re)designed product, a completed project, and (new) design history. More design and manufacturing knowledge of the team is obtained during the design process and this new knowledge is used as new steering input of the current or future processes.

The second phase encompasses a functional decomposition of the system. In such a functional model only those functionalities that are suitable for application within FROOM, will be present. Figure 4 presents a functional model for collaborative product development for one project and is a refinement of figure 3. The input and output characteristics of the black box work on the entire functional model. These characteristics are not shown in order to keep the model understandable.

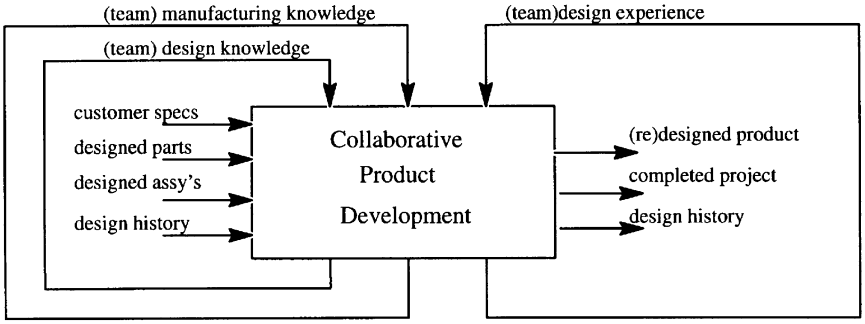

Figure 3 The collaborative product development system as a black box, with its input and output characteristics.

The communication function from figure 4, fulfilled by a communication mediator, can be divided into two main functions:

- conflict–based communication, initiated or triggered when designers create a conflicting overall product model.
- non conflict–based communication, started whenever necessary. For instance, to make a project planning, to organize a meeting or simply if information has to be requested which cannot be found in the design history or elsewhere.

Communication may be either uni–directional (e.g. e–mail) or multi–directional (e.g. video conferencing). This implies that a communication mediator should allow both. The first communication function, conflict–based communication, needs a tool which can signal the creation of a conflict. Detecting these conflicting constraints requires a constraint manager. Such a constraint manager should be present for each subsystem which then enables each end–user to come to a consistent and well–designed subassembly. This local constraint manager might encompass more than one constraint type. For the time being, we will restrict ourselves to parameter constraints.

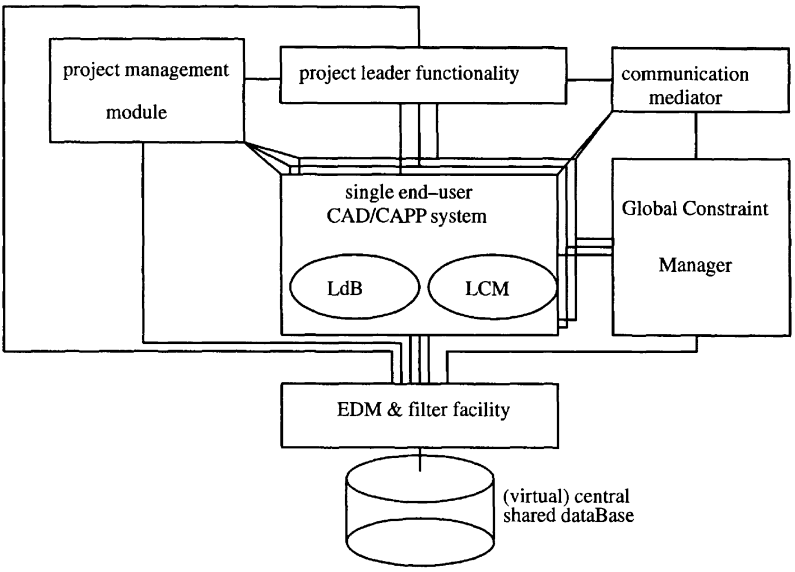

Figure 4 Extended functional model translated into a system architecture for collaborative product development (LdB = Local dataBase, LCM = Local Constraint Manager).

The presence of a local constraint manager (LCM) in each sub system provides possible solutions for the design of local (sub)assemblies. It enables the end–user to make a faultless i.e. acceptable design of his own local (sub)assembly. As can be seen in figure 4, each end–user has its own LCM. An acceptable design of a subassembly may not always lead to an acceptable solution when all the subassemblies are linked together in one overall product model. If constraint conflicts emerge during a global constraint verification, the design will not be acceptable. A global constraint manager is needed in order to signal the unacceptable designs that would be acceptable for the LCM's. Such a global constraint manager couples the subsystems and evaluates the interfacing constraints (on the links) between the subassemblies and other related constraints (if necessary). There is only one global constraint manager (GCM) for the integrated CAD/CAPP platform. If there are conflicting constraints, the global constraint manager triggers a signal to the communication mediator. The communication mediator then starts conflict–based communication between the end–users involved to provide them a view on the conflict. The filter will be set by default to the conflicting constraints because this is where the end– users are most likely interested in. During conflict–based communication it is allowed to adjust the filter in order to obtain a better look or understanding of the problem. This means that the communication mediator offers more than the possibility to communicate efficiently. It also provides transparency by allowing to adjust the filter(s) when necessary.

The different backgrounds of the disciplines (design or process planning or even disciplines within either of the two), result in different views on the same product model. The different views may be integrated by an Engineering Data Management (EDM) function to ensure that a seamless shared environment originates. In such an environment each group member can call for the data he needs hence obtaining transparency. The EDM function can be extended by the usage of filters. Filters are necessary in overcoming the different views on the same design between

the different domains. This means some kind of hybrid system, where EDM works centrally and the filters work locally.

The fact that constraints can be used very well in collaborative design, was already shown in the research by Bowen & Bahler and by Kuokka et al.. However, the approach by Bowen and Bahler did not match very well with the FROOM philosophy, which aims at preventing the designer from programming. Also, the research by Kuokka et al. based on conventional, iterative constraint solvers did not match very well as designers were given the freedom to be as cooperative as they would like to be. Therefore, another approach to the use of parameter constraints and parameter constraint satisfaction was proposed. This parameter constraint satisfaction was based on simulated annealing and has been implemented (section 5). The constraint satisfaction algorithm can be used to detect conflicts.

When the end–users somehow cannot reach a solution during negotiation, they can appeal to the project manager. The project manager then decides what solution is chosen. This may involve interference by the system user in a local constraint manager by setting certain constraints fixed.

Part of collaborative design is (project)planning. The planning function is shown in figure 4 and can be accessed by both system user and end–user. As during a project due–dates or deadlines have to be met, one can speak of time–constraints. A link may be present between the project related time–constraints and the product model related constraints mentioned earlier. However, their mutual influence is beyond the scope of this paper.

For implementation, only one constraint type respectively constraint solver have been considered: parameter constraints and Thornton's simulated annealing approach. This will be treated in the next section.

4. THE PARAMETER CONSTRAINT SATISFACTION METHOD BASED ON SIMULATED ANNEALING

Simulated annealing is an optimization search strategy which was invented in the early eighties by Kirkpatrick et al. (1983). Simulated annealing is based on the behavior of natural systems. There is an analogy with thermodynamics, with respect to the way that liquids freeze and crystalize or metals cool and anneal. This explains the name 'simulated annealing'. The process of simulated annealing can be visualized by a ball on a hilly surface. The ball represents the current energy state of the configuration where the surface represents the energy function (Thornton 1993), (Thornton & Johnson 1993). In Simulated Annealing the ball sometimes takes an uphill climb in order to find a global minimum. This is in contrast with other optimization techniques which are characterized by hill descent methods. This is shown in figure 5.

Thornton uses simulated annealing for the embodiment phase of the design process (Thornton 1993) and (Thornton & Johnson 1993). Her research resulted in a prototype tool called CADET, Computer Aided Design Embodiment Tool. A subsystem of CADET was used for constraint specification and constraint satisfaction in embodiment design. This subsystem is called SANCS, Simulated Annealing Network Constraint Satisfier. SANCS has a constraint network built from variables and constraints where the nodes of the network contain the variables and the links of the network contain the constraints. In SANCS, each link represents one constraint and connects all the variables in that constraint (Thornton 1993). An example of a constraint network is shown in figure 6. This network plays a central role in constraint satisfaction. When compared with other parameter constraint satisfaction techniques, such as the graph based approach by Serrano (1987), the one by Thornton has the following advantages:

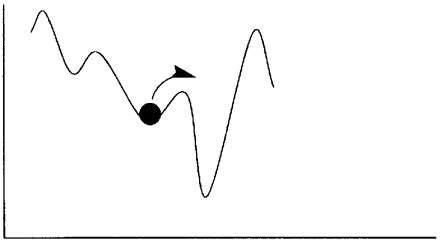

Figure 5 Simulated annealing as an optimizing algorithm capable of finding the absolute minimum where the ball represents the current energy state and the hills represent the energy function (redrawn after (Thornton 1993)).

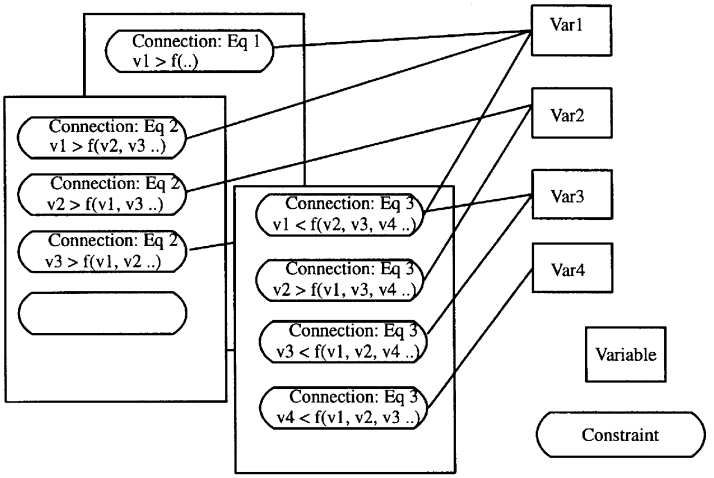

Figure 6 The constraint network (redrawn after (Thornton 1993)).

- No numeric instability.
- Support of interval algebra.
- Both equalities and inequalities can be handled.
- Solves under constrained sets of highly coupled, non–linear equations

In (Thornton 1993) and (Thornton & Johnson 1993), a more detailed overview of the simulated annealing approach that was applied is given.

5. IMPLEMENTATION

Two concepts were implemented: a parameter constraint solver based on simulated annealing similar to SANCS (de Graaff 1994) and a communication tool capable of allowing several different types of communication (Kuipers 1994). The procedure of the use of constraints for conflict–based communication is shown in figure 7 and can be described as follows. The constraints are specified in a constraint editor. However, due to the implementation of the editor not having been completed, tests were run on constraints listed in a file. The constraints are then solved and if any

conflicting constraints are detected, the communication mediator is started. This is the so–called constraint–based communication which is oriented towards initiating communication formally. Without any conflicts, the results of constraint satisfaction are presented. Naturally, voluntary, informal communication can be started too. The FROOM environment was used, i.e. C++, X–Windows/Motif, Acis and the Builder Xcessory tool (Integrated Computer Solutions 1994). In the following, the communication tool is elaborated in section 5.1 while the implementation of the constraint solver is detailed in section 5.2.

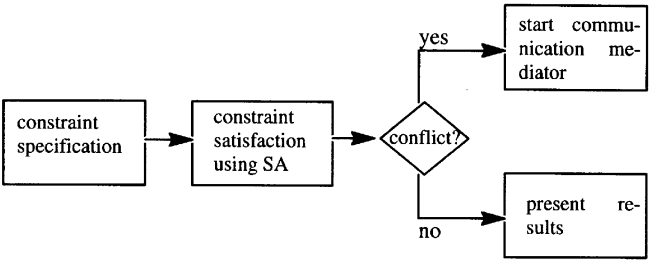

Figure 7 Implemented procedure.

5.1 Communication tool

The communication tool is divided into a uni–directional and a multi–directional part, as mentioned earlier in section 3. The window of the communication tools is shown together with the FROOM window in figure 8. In the left column the buttons for uni–directional communication are placed, and in the right column the buttons for multi–directional communication are located. A possibility of multi–directional communication is video conferencing. The video conferencing tools that are used, are public domain software and can be accessed via the Mbone Homepage (1994). Finally, in a horizontal bar at the bottom of the window, other functions, like the help function and the design history record function, are placed. However, the design history record button does not yet work; the design history functionality as currently present in FROOM has not yet been extended to support collaborative engineering (Salomons et al. 1995d).

5.2 Constraint solver

The simulated annealing approach by Thornton was implemented using the object–oriented C++ language (de Graaff 1994). During implementation of the parameter constraint solver some problems occurred. Thornton gives rules for the rearrangement of constraints in order to build a constraint network as shown in figure 6. However, these rules are not applicable in every situation (Thornton 1993). These exceptions were not implemented and evaluated in the experiments by Thornton. An example of such an exception is the following equation, which was already identified by Thornton:

$C < (A + D) * (A + B)$.

Suppose we want to rearrange this equation to an equation of the term A > ... It can easily be seen that A cannot be solved. This means that for such situations an alternative has to be provided. This can be done by the introduction of a new variable. The procedure for this introduction is to first replace (A+B) by Q. The equation can now be rearranged to: $A > (C/Q) - D$. Finally, add a new constraint: $A = (Q–B)$.

A sophisticated constraint satisfaction algorithm should provide for this. However, it may be difficult to program an algorithm that recognizes the situation mentioned above and provides

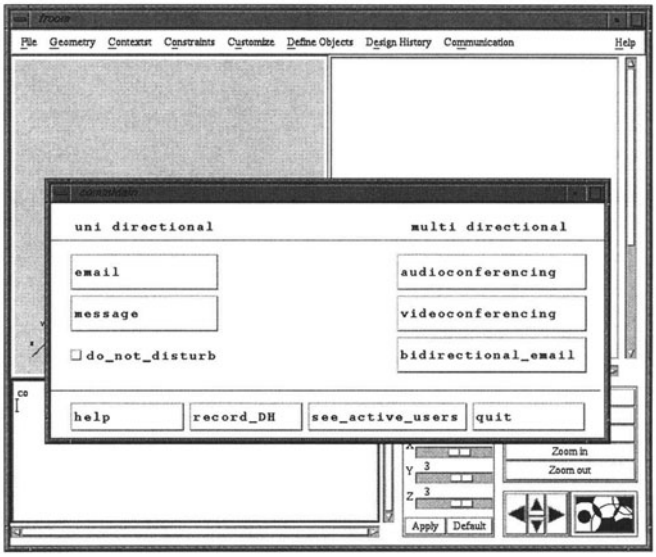

Figure 8 Top level user interface of the communication possibilities offered to the end–user.

solutions for it at the same time. For the time being, this task may be directed to the end–user who then could use the constraint editor in order to overcome such an incapability of the constraint solver. At the moment the introduction of new variables is done by hand.

Rearrangement may lead to another additional, preventive measure in the source code. Take the following example:

$$A = (D^2+K).$$

Solving for D gives:

$$D = \sqrt{(A - K)}.$$

This means that an additional requirement has to be solved: A>K. However, during the satisfaction of the constraints, parameter K can obtain (temporarily) a higher value than parameter A. The equation is not solvable as square–roots of negative values are not allowed. This problem has been eliminated however. Details are provided in (Kuipers 1994).

In the following, only conflict detection is explained in more detail. Generally, three different types of conflicts in constraints can be discerned:

- Conflicts initiated by a wrongly specified constraint. This type of conflict is introduced during constraint specification. This type of conflict has to be detected in the constraint editor before constraint satisfaction is applied.
- Conflicts initiated by a false range of variables. E.g. x>6 and x<5. Such conflicts are also introduced during constraint specification and are checked before constraint satisfaction is applied.
- Conflicts that occur during constraint satisfaction. These are the most interesting conflicts, which are also detected by SANCS. Details are provided in (Kuipers 1994).

6. DISCUSSION

Performance of the constraint solver was fair but not in real time as a user would like to have it. Tests were run on constraint sets of approximately 20 constraints with 50 variables. Depending on the range of the variables, it took about 2 – 5 minutes to solve these sets or detect a conflict on Silicon Graphics Indy workstations with R–4000 100MHz MIPS processor.

Up to now, the experiments on simulated annealing were applied only within the FROOM system; no CAPP system was involved.

Three different types of constraint satisfaction have (partly) been implemented in FROOM: DOF analysis for geometric constraints, Simulated Annealing for solving parameter constraints and the TTRS method for the solution of tolerance constraints.

As a result of the selection of three different constraint satisfaction techniques, the interdependence between these three techniques must be considered. If one constraint type is changed, added or deleted and this change is evaluated in the corresponding constraint solver, what effect can it have on the other constraint types? If there is an effect, does it involve the necessity of re–evaluating constraints of other constraint types? A "multi–brid" constraint solver is wanted, combining the different constraint satisfaction techniques seamlessly, offering highly intelligent support to the users. Such a multi–brid constraint solver seems highly desirable in order to support a more sophisticated constraint based communication facility for the collaborative product development facility in FROOM.

Let us first reconsider the constraint satisfaction techniques which have been selected for use in FROOM and focus on their differences and commonalities. It seems especially worthwhile to investigate DOF–analysis vs. parameter constraints as both of these can be related to geometry. Also, a comparison of DOF–analysis with the variational constraint method by Clément et al. seems interesting because they have a common background in kinematics.

DOF–analysis vs. parameter constraint satisfaction

Kramer's DOF–analysis is focused on geometry related constraints only. These are solved using geometry related domain knowledge. Thornton has only been looking at mathematical constraints, which sometimes are related to geometry making them geometric constraints as well. However, because of the fact that the domain knowledge of geometry is not used in satisfying the mathematical constraints in the Thornton approach, this can lead to unexpected or corrupt geometry when the (geometric) constraints are not correctly specified. Nevertheless, parameter constraints are necessary in addition to purely geometric constraints for expressing e.g. relations between stresses, forces, material properties, dimensions etc..

If a parameter in a parameter constraint is changed, added or deleted and if this parameter represents some (previously established) degree of freedom in a DOF constraint network, the DOF constraint has to be re–evaluated. On the other hand, if some DOF constraint is added, deleted or changed, like an assembly relation or a feature internal relation, and a parameter is related to the constraint, then the parameter constraint expression(s) have to be re–evaluated.

DOF–analysis vs. TTRS variational constraints method

The kinematic method by Kramer resembles in a way the method of variational constraints by Clément et al.. One difference is that Kramer takes into account large displacements and large rotations while Clément et al. consider small displacements and small rotations. Both methods use a kind of matrix in which domain dependent knowledge is stored. Kramer uses the plan fragment table, in which rotational and translational degrees of freedom are kept (Kramer 1992). Clé-

ment et al. use a matrix of surface associations in which 7 types of elementary surfaces are combined, resulting in 28 possible associations called TTRS (Clément et al. 1993, 1994). The table by Clément et al. also indicates the nominal dimensions that have to be specified for the instantiation of tolerances. When looking at it from the DOF–analysis point of view, this nominal dimension might be regarded as a dimensional degree of freedom. However, usually the geometry is already completed (all dimensions known), before tolerancing starts. During the process of tolerancing, sometimes nominal dimensions may have to be changed. It must be noticed that in general a change of tolerance–value does not affect nominal geometry whereas a change in nominal geometry may cause a change in tolerance value.

Parameter constraints vs. TTRS variational constraints method

Variational constraints (tolerances) sometimes have a nominal dimension associated with them. If the nominal dimension is changed as a parameter in a parameter constraint equation, the type of tolerance will not necessarily have to be changed. However, if the nominal dimension is changed, it may be necessary to reconsider the tolerance value. If, on the other hand, the tolerance changes – either type or value – this has in general no impact on the nominal dimension associated with the tolerance and therefore on any parameter constraint in which the nominal dimension appears as a parameter.

Currently work is being performed in order to start realizing a "multi–brid" constraint solver based on the principles as described above.

7. CONCLUSIONS AND RECOMMENDATIONS

A design and a partial implementation of a collaborative product development module for CAD and CAPP systems has been presented. Collaborative product development in this module is based on both the use of constraints and on communication on a voluntary basis. The prototype implementation proved that constraints can indeed be used as a basis for communication in collaborative product development. Constraint conflicts are used to start communication. This will lead to a maximum of cooperativeness with a minimum of communication thereby maximizing the transparency, in accordance with the definition of concurrent engineering from section 1. Therefore, the efficiency of concurrent engineering, which is measured by how long it takes to find and correct a design mistake, is enlarged by the use of constraints as a basis for communication in collaborative design. However, the partial implementation needs to be completed in order to allow more complex and realistic cases of collaboration to be supported. A unified constraint solver, based on other techniques than simulated annealing alone like DOF–analysis and Clément's tolerancing solver should be developed to support extended cases of conflict–based communication. The efficiency of the simulated annealing algorithm could be improved. Also, tests in actual practice still have to be made to verify the preliminary results.

Another future research topic related to collaborative product development is project planning. More research has to be performed into the feasibility of an active, computer supported project planning tool. Also, a link between the Design History tool and the communication mediator is a future topic of research.

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