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An Integrated Tool for Designing Space Trusses

Système de conception pour le projet de structures tridimensionnelles

Ein integriertes Entwurfssystem für Raumfachwerke

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SUMMARY

The integration of specialised programs for the design of space frames has been realised in a Windows-based environment. The design system provides support for all phases of design, i.e., for conceptual design and detailed design as well as for archiving and retrieval of projects completed. In order to enable a fast cost estimation, a neural network application has been added. Thus, this program is able to learn from past projects in order to predict the cost of new structures.

RÉSUMÉ

L'intégration de programmes spécifiques pour le projet de structures tridimensionnelles est réalisé dans un environnement Windows. Le système de conception apporte une aide à tous les stades du projet aussi bien pour la conception et le détail que pour l' archivage et la recherche de projets achevés. Une application de réseau neuronal est incluse en vue d'une rapide estimation des coûts. Ce programme est en mesure de tirer les leçons de projets réalisés pour estimer les coûts de nouvelles structures.

ZUSAMMENFASSUNG

Die Integration von Spezialprogrammen für den Entwurf von Raumfachwerken wurde innerhalb einer Windows-Umgebung verwirklicht. Das System unterstützt in allen Entwurfsphasen, d.h. sowohl beim konzeptionellen und detaillierten Entwurf als auch beim Archivieren und Suchen bereits abgeschlossener Projekte. Um eine schnelle Kostenschätzung zu ermöglichen, wurde eine neuronale Netzwerk-Anwendung hinzugefügt. Dieses Programm ist in der Lage, aus bereits abgeschlossenen Projekten zu lernen, um damit die Kosten für neue Tragwerke voraussagen zu können.

1. INTRODUCTION

Space frames like the ZÜBLIN space frame system are regular steel structures made of prefabricated spheres and rods, connected by bolts. Such filigree spatial or plane bearing structures are frequently used to cover large areas without introducing intermediate supports (Fig. 1).

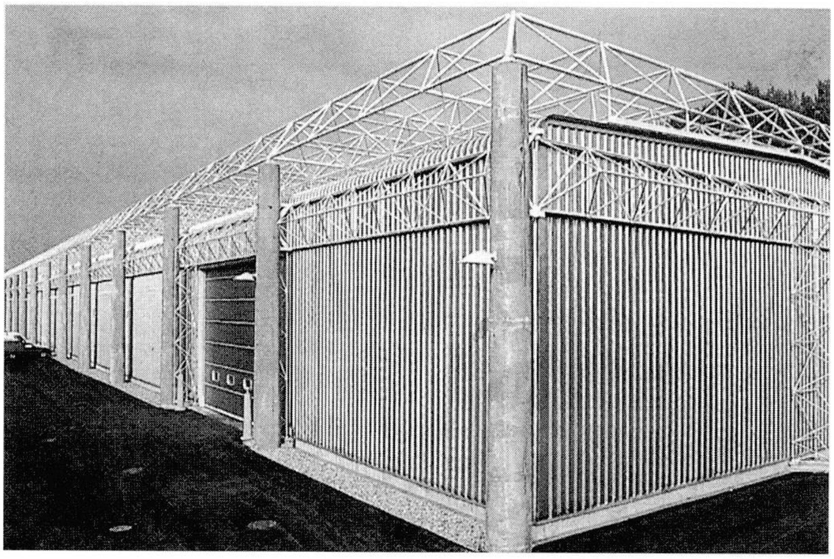

Fig. 1 Space frame roofing of a factory in Kempten, Germany

Design and manufacture of space frames belong to a field of engineering design where substantial computer assistance is available at different stages:

- modelling
- structural analysis
- construction
- cost evaluation
- manufacturing.

Specialized computer programs are available for each phase [1]. However, integration of these programs poses trouble in practice. In the course of designing and comparing alternative solutions, a great deal of routine and time-consuming work like generating, editing, transferring, evaluating, compressing and archiving of data is involved. In order to separate necessary design decisions from this routine work, the integrated design system SpaceFrame has been developed. This system manages the automated data flow between the specialized programs.

The tendency towards developing integrated tools prevails nowadays in the software industry in general and the Computer Aided Design is no exception to that trend. Most systems appearing contemporarily are based on the Object Oriented Programming paradigm (see [2], for example). Using object oriented languages (C^{++}, Smalltalk) together with CAD and database systems, complex structures are modelled according to classification and aggregation concepts. In a similar way, object-oriented languages can serve for the representation of design knowledge, e.g. codes and standards [3]. The object oriented concept will lead to new development of design applications. The integration of existing analysis and CAD programs, however, can be difficult because most of these programs have been realized without respect to the object oriented concepts.

Therefore, the integration of design software in complex fields of design in a heterogeneous environment can be achieved by so-called agents. Agents are computer programs which perform the communication between several applications. In facility engineering, the development of an agent-based framework based on interface standards is used to integrate different users (architects, engineers), different design software and different hardware [4].

2. DESCRIPTION OF PACKAGE

The integrated system SpaceFrame is based on a design model following the process model paradigm [5]. Since representation of the design structure is embedded in the application modules, the object oriented paradigm [6] is of less importance in this design model. Input and output of the specialized programs TRIMAS G, STARA, ZUBER, TRIMAS A, ZEICON are modelled as data flows.

TRIMAS G	graphic preprocessor, generation of structures, e.g. spatial frames, folded plates etc. [7]
STARA	linear and nonlinear analysis of spatial frames [7]
ZUBER	dimensioning of members, construction and manufacturing charts [1]
TRIMAS A	graphic postprocessor, evaluation of results, e.g. displacements and stresses [7]
ZEICON	CAD system for structural engineering [7]

As weights and stiffnesses of the members are not known a priori, STARA (structural analysis) and ZUBER (dimensioning of members) are usually run in several iterations. This is illustrated in Fig. 2 and 3. The structural analysis is performed with initial member sections, each member having the same section. The structural analysis leads to member forces which serve as input for the dimensioning of members. The member sections are chosen from a member catalogue and serve as an input for a new STARA run. The iteration is repeated as long as previously assumed member sections and member sections found by ZUBER are the same.

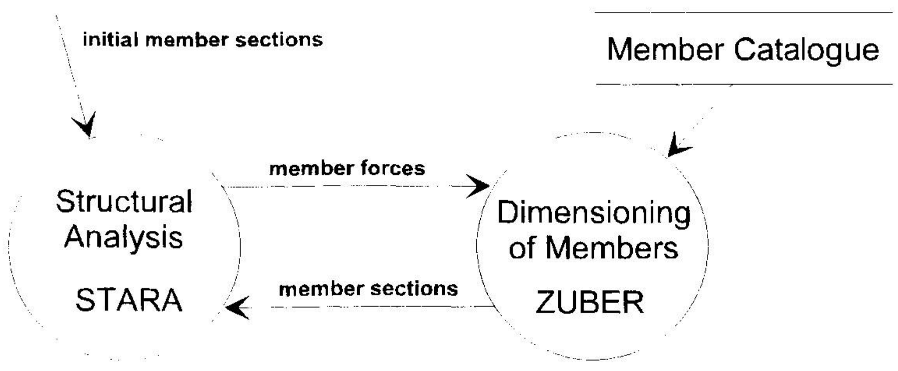

Fig. 2 Data Flow Diagram of the STARA-ZUBER Iteration

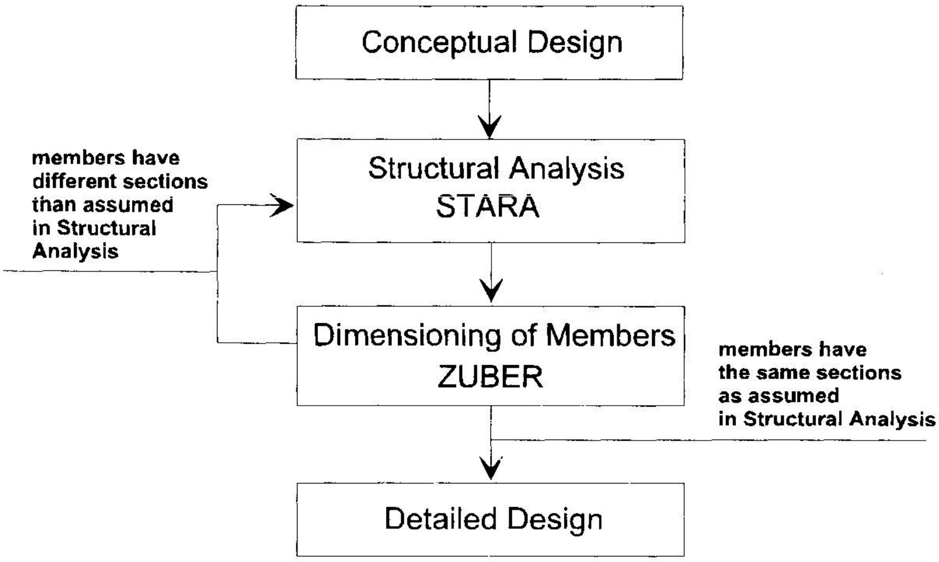

Fig. 3 State Transition Diagram of the STARA-ZUBER Iteration

Emphasizing the information flow, the approach of SpaceFrame is similar to the agent-based approach. The existing programs for analysis and CAD are embedded in one environment which allows the transfer of information from one application to the other. However, the complexity of knowledge and data is manageable using straightforward interface formats. E.g., the output list of the dimensioning program ZUBER serves as input for the CALCULATOR module and the CALCULATOR list can be directly read by the FILTER module. The main focus lies in capturing the design process from the top to the bottom, i.e. from the early design stage to the archiving of completed projects.

The goal of SpaceFrame is to cover all activities of structural engineering in a single environment. In the early design stages, i.e. for conceptual design, the GENERATOR and ARCHIVER moduli are mostly used. They support the user in checking alternative solutions, e.g when a proposal for bidding is to be prepared. In order to gain flexibility, these moduli are complemented by the LEARNER and ESTIMATOR modules.

LEARNER	creation and update of a cost estimation data base
ESTIMATOR	estimation of cost and weight based on a few input parameters, e.g. length and width

SpaceFrame combines the above mentioned moduli in a windows-based environment, adding the following features:

GENERATOR	quick generation of space frames out of a few input parameters, e.g. length, width, height, type of support, loading
CALCULATOR	calculation of prices for manufacturing, assembly, etc.
FILTER	compression of results for characteristic parameters, e.g. weight, manufacturing cost, assembly cost, etc.
ARCHIVER	storage and retrieval of compressed data from past projects

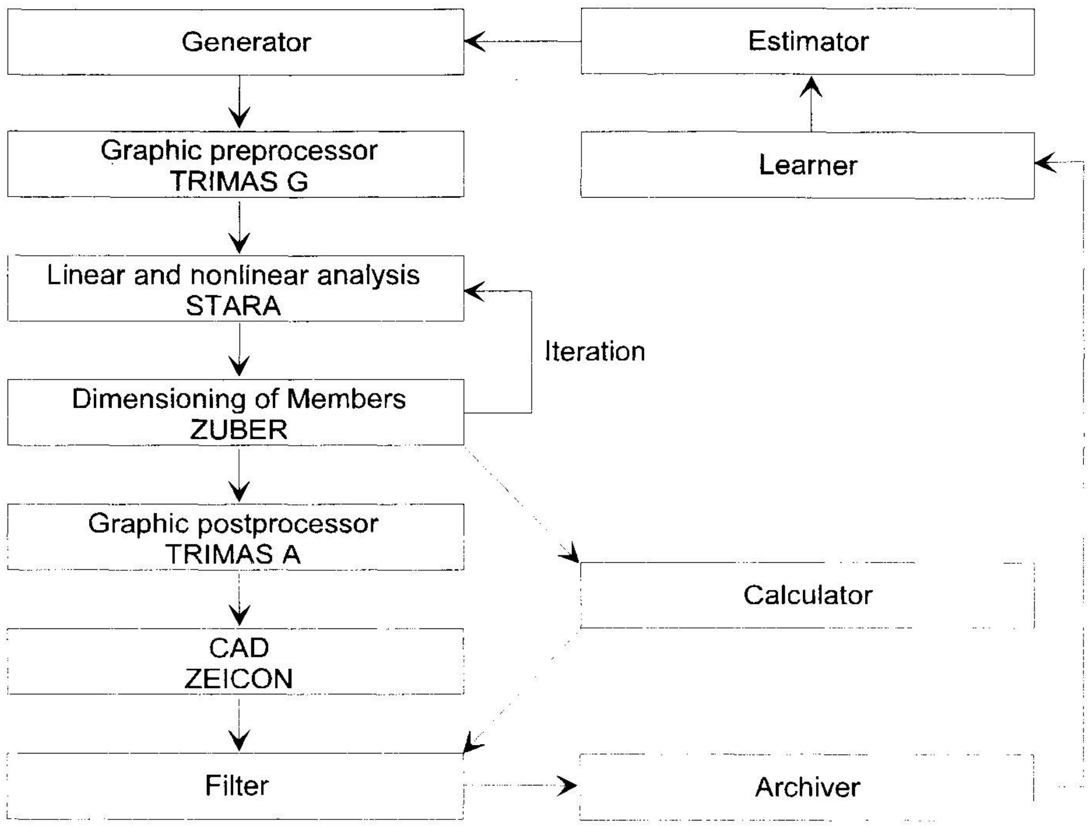

Fig. 4 Block diagram of SpaceFrame system

3. COST ESTIMATION MODULE

In order to be able to evaluate the total cost of the structure quickly, it was decided to use simulated neural networks. Their ability to learn from examples seems to be well suited for the present case, where a sufficiently large set of structures of known total cost is either available from past experience of the user or can easily be prepared by applying the analysis-design part of our system. Our previous experience in applying neural networks in structural engineering ([8, 9]) confirms that they can efficiently complement conventional AI-tools, like symbolic reasoning systems and heuristic search algorithms.

Our aim is to learn a continuous mapping $f: \boldsymbol{A} \subset \boldsymbol{R}^{n} \rightarrow \boldsymbol{B} \subset \boldsymbol{R}^{m}$ from a bounded subset of design attributes $\boldsymbol{A}$ to a bounded subset of evaluation attributes $\boldsymbol{B}$. There are several models of neural networks which could be considered as candidates for solving such a problem [10]. The most frequently used is the multilayered feedforward network with backpropagation of error (the BP-network). It admits continuous real-valued input/output data but suffers from local minima of the error surface and requires considerable time-consuming learning. Hence, we committed ourselves to the more efficient Fuzzy ARTMAP paradigm proposed by G.A. Carpenter and S. Grossberg [11].

The antecedent of the Fuzzy ARTMAP was the ART-1 model able to categorize binary coded patterns in an unsupervised manner. This rather complicated model stored learned categories in the feed-forward and feed-back weights linked to the connections between input and output layers. After a new pattern was presented to the network, a multiphase processing started. First, the winning output was determined by lateral inhibition similar to that of the Kohonen layer. Then the winning node was subjected to the similarity test (vigilance test). This test consists in comparing the similarity measure:

$$S = |(\mathbf{x}\ \mathit{and}\ \mathbf{t})| \ / \ |\mathbf{x}|$$

where $\mathbf{x}$ is the input vector, $\mathbf{t}$ is the vector of feed-back weights for winning node and $|\ .\ |$ means norm, to the user defined vigilance threshold.

The Fuzzy ART model is simpler since it uses only feed-forward weigths. Its input can be real-valued because the logical operators *and*, *or* applied to binary patterns in the ART-1 were replaced by their fuzzy counterparts *min*, *max*. Thus each category is treated now as a fuzzy set [12] and the vigilance threshold controls the level of fuzzinesss of the classification preferred by the user.

The next step was to combine two Fuzzy ART networks with an associative memory called map field (Fig. 5). Such a 3-layered structure is able to learn in a supervised manner, like feed-forward networks with the backpropagation of error. During learning process the Fuzzy ARTMAP receives a large number of training pairs ($\mathbf{a}^k$, $\mathbf{b}^k$). The input $\mathbf{a}^k$ is categorized by the network a and the desired output $\mathbf{b}^k$ by the network b. The correspondence between a-categories and b-categories is coded in a kind of associative memory, called the map field. The size of an individual category is governed by the vigilance parameter ρ. During learning the user selects such a value ρ_b that each $\mathbf{b}^k$ is assigned a separate category. The network automatically adjusts the vigilance parameter ρ_a: if current $\mathbf{a}^k$ and $\mathbf{b}^k$ do not match each other on the map field, then ρ_a is slightly increased and either another a-category is found or a new a-category is generated. As a result of fine tuned dynamics, the details of which can be found in [11], the network minimizes the predictive error and maximizes generalization. It is important for practical applications that Fuzzy ARTMAP indicates unrecognized cases, contrary to the BP-network.

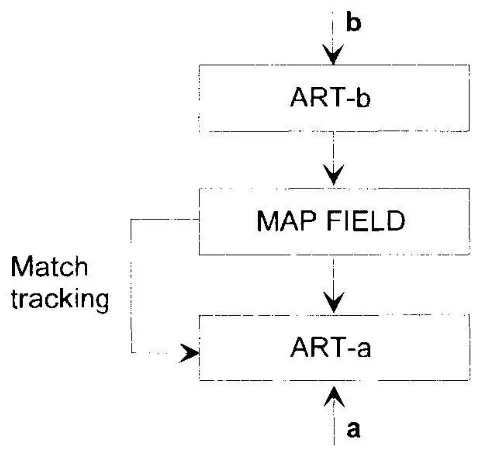

Fig. 5 Conceptual scheme of the Fuzzy ARTMAP network

4. EXAMPLE

Since archiving of the (approx. 200) completed space frame projects realized by Züblin is not yet finished, the generation of the required training set was carried out using the GENERATOR module. Fig. 6 shows the user interface for input. The user has to set the main input parameters, i.e. length *(Länge x)*, width *(Länge y)*, height *(Höhe z)*, grid *(Teilung x, Teilung y)*, load *(Last obere Ebene, Schnee)*. Default values, e.g. for cross-section, can be changed if desired. After having specified the input parameters, analysis is commenced with the tool panel (Fig. 7), providing all options according to Fig. 4.

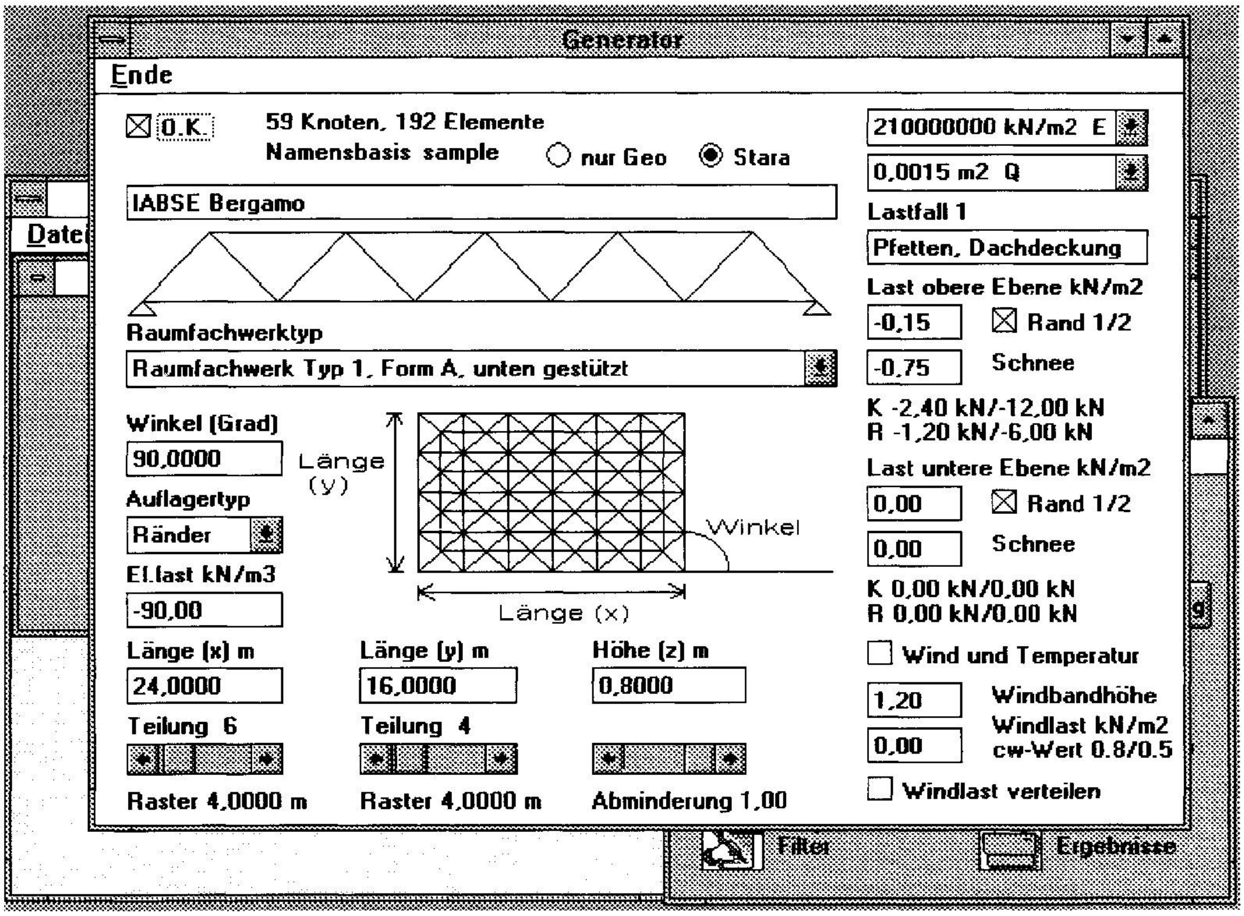

Fig. 6 GENERATOR user interface

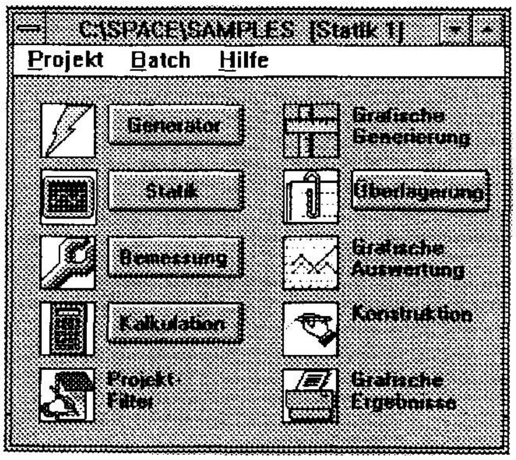

Fig. 7 SpaceFrame Tool Panel

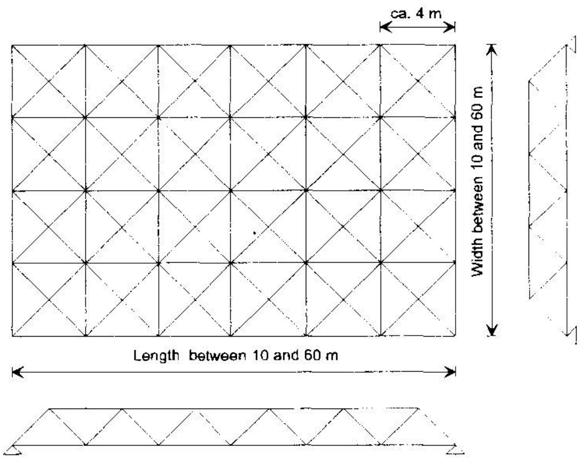

Fig. 8 Layout of the example

In order to evaluate the accuracy of cost estimation, the series of 200 roofings were generated randomly within the following constraints (Fig. 8):

- both length and width were taken between 10 and 60 m
- loading equal to 0.90 kN/m^2 (dead load, snow)
- height equal to 1/20 of the smaller dimension
- grid cell was kept to approx. 4 X 4.00 m

Each roofing was completely analyzed, optimized and dimensioned by SpaceFrame. After that the total cost of the structure was calculated according to the specification of required parts and the list of their prices. In this manner, a data set consisting of 200 triples (L_x, L_y, *cost*) was obtained.

According to the usual procedure of supervised learning, the data set was split into 2 parts: a training subset and a testing subset. The ratio between their cardinalities was taken as 2 : 1 . The first part was presented to the Fuzzy ARTMAP network 5 times allowing it to adjust the weights. These weights were subsequently frozen and the network was used to estimate the cost of each of the members of the testing set given the dimensions L_x and L_y of the structure. The following results were obtained:

Error (%)	Sequence 1	Sequence 2	Sequence 3
Mean global	5.6	7.5	5.6
Max local	17.6	15.1	15.2

The mean global error was calculated for the entire training set. The maximum local error was observed for a particular space frame. In order to check whether the learning depends upon a sequence of training examples, the experiment was conducted for 3 randomly generated sequences of data.

The quality of prediction depends mainly upon the completeness of the training set. Despite the modest number of 140 examples presented to the network, the mean cost estimation accuracy turned out to be in the order of 6%, which is quite sufficient for practical purposes. It is worth noting that the computational cost of learning is small (5 epochs) and that the response of the trained network is immediate.

5. CONCLUSION

Design integration is achieved by combining specialized programs under a windows-based environment. Following the process model paradigm, the SpaceFrame system could be realized within a few months. Intensive discussion with practitioners was a main element during work, leading to a good acceptance. Further work is aimed at the specification of the design process of structures in a formal way, using methods proposed in [5, 6].

Experience gained so far using the cost estimation module confirms our decision of applying the Fuzzy ARTMAP network for solving this particular task. Sufficient accuracy for the stage of tendering and preliminary design was achieved with 5 training cycles (approx.) involving 200 examples. It is of considerable advantage that the Fuzzy ARTMAP network learns incrementally. Consequently, knowledge gained from new cases can be incorporated easily.

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