XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

Cost Estimate in the Design Phase through an Expert System Prototype

Jonny Carlos da Silva, Dr. Eng.
jonny@emc.ufsc.br
LASHIP- Laboratory of Hydraulic and Pneumatic Systems
Mechanical Engineering Department- Federal University of Santa Catarina
Po.Box. 476-Florianópolis-SC-Brazil-CEP 88040-900

ABSTRACT: It has been widely recognized the increasing importance that cost has received in the design process. Gradually, more designers are becoming aware of considering cost aspects, as early as possible, in the development process, i.e. design for cost. In a concurrent engineering perspective, cost aspects must be integrated in the design process since the product conceptual stage. Moreover, concurrent engineering embraces expertise from different areas. In hydraulics, such expertise includes knowledge gathered from several sources, e.g. manufacturers, textbooks, designers. These arguments support both the demand and feasibility of developing an expert system to assist the design of hydraulic systems considering a concurrent engineering perspective (Silva,98a). This work presents an expert system prototype that integrates concepts from Design Methodology, Artificial Intelligence and Hydraulic System, developed using CLIPS. The development applied Internet technologies for knowledge harvesting and user interface. First, this paper discusses the relevance of hydraulic systems for industrial equipment performance, it follows a description of the prototype. Finally, the paper focuses on how cost was dealt with in the present stage and challenges ahead to involve more knowledge sources in order to develop a cost estimate tool, allowing the prototype expansion based on interaction with industry.

Key Words : *Expert System, Cost Estimate, Design, Hydraulics*

1. INTRODUCTION

Due to the needs originated from intense market transformations, i.e. increasing competitiveness, technological advances as well as economic globalization, more companies have applied Concurrent Engineering techniques. In this context, the time to market is as important as the product quality, some researches show that 80% of a market for a new product is shared with the first two companies which launch the product (Brazier,90).

In order to cope with this environment, multidisciplinary teams grouping, for example, engineers, designers and market analysts are being integrated to search for ways of creating quickly and more efficiently new products through collaborative Concurrent Engineering efforts. There are many definitions for concurrent engineering, one of them is quoted as follows:

Concurrent Engineering is as a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements (Klement,93).

As can be seen, in the context of concurrent engineering, cost is one of attributes to be taken into consideration as early as possible, in order to avoid great changes in the design in the late stages of the design process. Despite its great importance, this feature appears to be one of the most difficult product aspects to be embraced in the general design process, perhaps this consideration is due to the fact that information regarding costs should be considered strategic for the designer (or product developer) or even that such information requires knowledge not easily available in the working environment. Moreover, such knowledge may be scattered throughout the enterprise rather than concentrated in few individuals.

Considering the design of fluid power systems, a computational tool to support such task involving a concurrent engineering perspective can provide guidelines for maintenance, overall design, sizing facilities, alternative comparison, etc. (Silva,99). This work is based on a prototype expert system to support the design of hydraulic system focusing on concurrent engineering aspects (Silva,98a). The system was conceived in Brazil, implemented in England, through a collaboration scheme between Federal University of Santa Catarina (UFSC) and Lancaster University. The prototype was extensively validated by experts from industry and academy, in the United States, England and Brazil.

Based on the experience gathered with the prototype exposure, this paper proposes some issues on the system expansion to embrace specific rules regarding cost estimate and guidelines to design with cost awareness. The paper is divided into the following sections: some relevant aspects of hydraulics for equipment performance are presented. It follows a brief description of the prototype functionality. In order to present the feasibility of such expansion, the paper discusses some key concepts necessary to demonstrate the system expandability. These concepts include: knowledge representation paradigm, rules and object oriented modeling (Silva,97a), and incremental process development (Silva,97b). Then, it describes some potential issues on which a cost estimate tool would be of use. Finally, the work discusses how these issues will be addressed in order to expand the system.

2. RELEVANCE OF HYDRAULICS

In its 50th anniversary issue, Hydraulics & Pneumatics Magazine presented a comprehensive overview of areas on which fluid power has given a substantial contribution. They range from mining, construction, machine tools, aerospace, agriculture etc. The issue also presented some examples of how design plays a vital role in fluid power area, such as: packing high power into small space as the essence of coal mining equipment, where reliability is also of great importance, for unscheduled maintenance cannot be tolerated. In response to these demands, equipment designers relay more and more on integrated hydraulic circuits (IHCs) for underground mining equipment. IHCs combine valves and other components into single manifold block to save space, eliminate much of the interconnecting hose, tubing, and fitting otherwise required, and enhance maintenance. When a malfunction does occur, technicians simply replace an IHC manifold rather than troubleshoot the entire system to find the faulty component. Reliability is also improved by eliminating the number of hose assemblies and line-mounted valves used- components subject to heavy wear and tear in rugged mining conditions (Schneider,98).

Based on the aspects necessary to properly design hydraulic systems, it becomes evident that such activity involves a considerable degree of expertise, which is not always available in an acceptable cost and time scale. This means that a decision making supporting tool may facilitate the design task even when performed by an expert, or indeed educate an inexperienced engineer on the field. A comprehensive study on the feasibility and applicability of computational tools to support the design of hydraulic systems was made in (Silva,98a).

3. PROTOTYPE DESCRIPTION

This section gives a brief description of the prototype. The prototype assumes the user has a generic background on mechanics, but without requiring specific knowledge on fluid power. Thus, the user must be able to describe the machine features based on its qualitative and quantitative attributes which are expressed only in mechanical terms, in other words they are domain independent, it means their description is separated from the actuation system, regardless if this system is hydraulic, pneumatic, electro-mechanical or hybrid. This feature, defined in the project conceptualization, turned out to be a fundamental aspect to the system expandability, for with the machine functionality decomposed in a set of load objects containing only mechanical aspects, this module of the prototype, i.e. the load objects, will be reused for future projects in different domains. The machine functionality breakdown also suggested a methodological approach to the design process. Figure 1 depicts how the machine structure is specified according to the set of its actuation points, represented as load objects in the prototype.

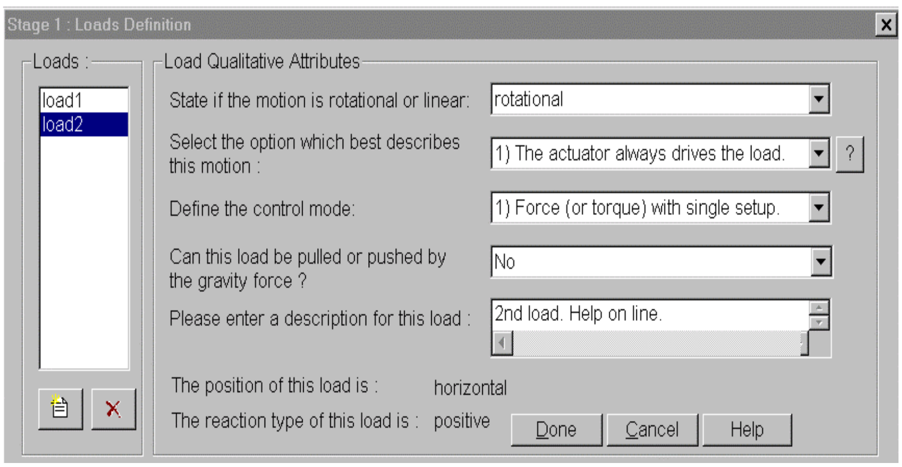

Figure 1- Machine Description per load.

As shown in figure 1, each load is specified by a set of attributes. The load properties are presented in an easy form, with a help-on-line facility. Each load is individually described, first in a qualitative form and then with their numerical parameters, through another dialog box. This distinction was made to suggest the user an overall conceptual analysis of design alternatives for actuation and power supply circuits, **before** actually considering numerical parameters. This feature has proven to be unique and of great use in demonstrating a concurrent engineering perspective to the process of designing a hydraulic system. The numerical parameters are entered also through a user-friendly dialog box which prompts the parameter set according to load domain, i.e. linear or rotational. Although only these domains were modeled, during the system development a significant modularity was conceived in order to allow the system expansion, more issues on that can be found in (Silva,98b).

In order to summarize the prototype description, its present functionality can be listed on the following items:

1. Prompts the user to respond interactively to determine the machine requirements in a friendly form, i.e. without requiring specific knowledge on hydraulics.

2. Automatically generates, based on well proven principles of circuit design, a set of feasible circuits for consideration by the designer.

3. Allows the preliminary ranking among alternative solutions from general attributes.

4. Allows the change of Power Supply unit, redefining the component lists.

5. Calculates the power supply demand based on load attributes (force, speed, etc.).

6. Handles servo-hydraulic circuits as feasible alternatives.

7. Generates topological dynamic models for simulation tailored for a specific simulation package (Silva,97d).

8. Displays the circuit schematics and descriptions through automatically generated HTML pages which can also be viewed via an INTERNET browser (Silva,97e).

9. Offers a fluid selection tool, database type, through which the user can search via keyword combination (e.g. fire and mining), obtaining as result a list of suitable fluid types with their ISO specification, applicable and non-applicable areas. This is a vital aspect for maintenance, because over half of all hydraulic system problems have been traced directly to the oil (Esposito,97).

Next figure presents, in a simplified form, the overall prototype structure.

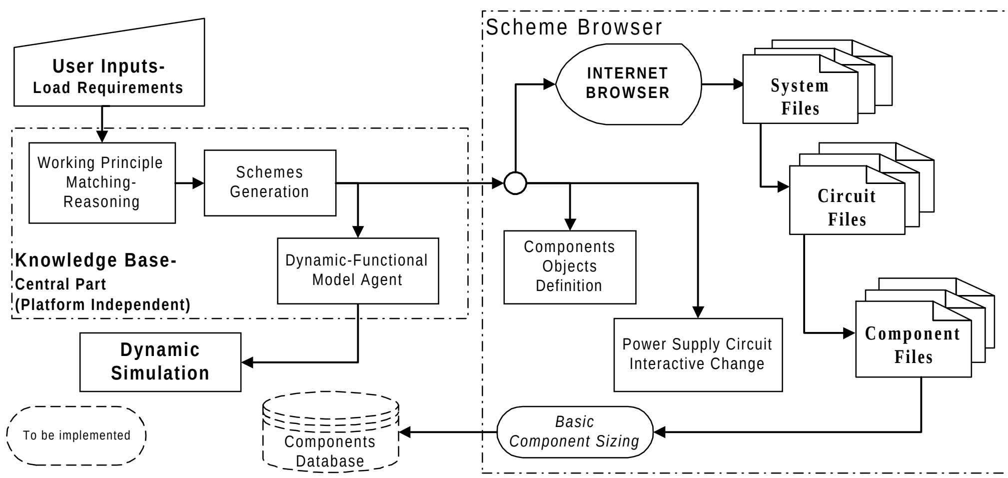

Figure 2- Prototype Functional Structure.

The prototype overall functional structure depicted in figure 2 includes the user interface and knowledge base framework. The system was implemented in CLIPS (C Language Integrated Production System, a shell tool developed by NASA) using its Object-Oriented Language- COOL (Giarratano,94).

As shown in figure 2, through a *working principle matching reasoning*, based on well established design principles, a machine list of requirements, mapped unto a set of load objects, activates their corresponding rules. These rules define a set of working principles, i.e. circuit objects, necessary to accomplish each load. It is known that some combinations of load attributes can be matched by different types of circuits, for example types bleed-off and meter-in flow control circuits can satisfy the same attribute combination, though they are functionally different working principles. Thus, for a specific set of loads different solutions can be obtained. Therefore the prototype combines all circuit objects, accordingly, to generate schemes that satisfy the overall machine functionality.

Once the schemes, i.e. the hydraulic system objects, are created, they can be analyzed from different perspectives, depending on the user's requirement. Although the user is relatively unrestricted to continue the design, for example to include quantitative parameters, the prototype recommends a next step which corresponds to investigate and compare the different design solutions. As the prototype automatically generates all objects representation in HTML format (Silva,97e), the design solution analysis is performed in a user friendly form via an INTERNET browser, as shown in figure 3.

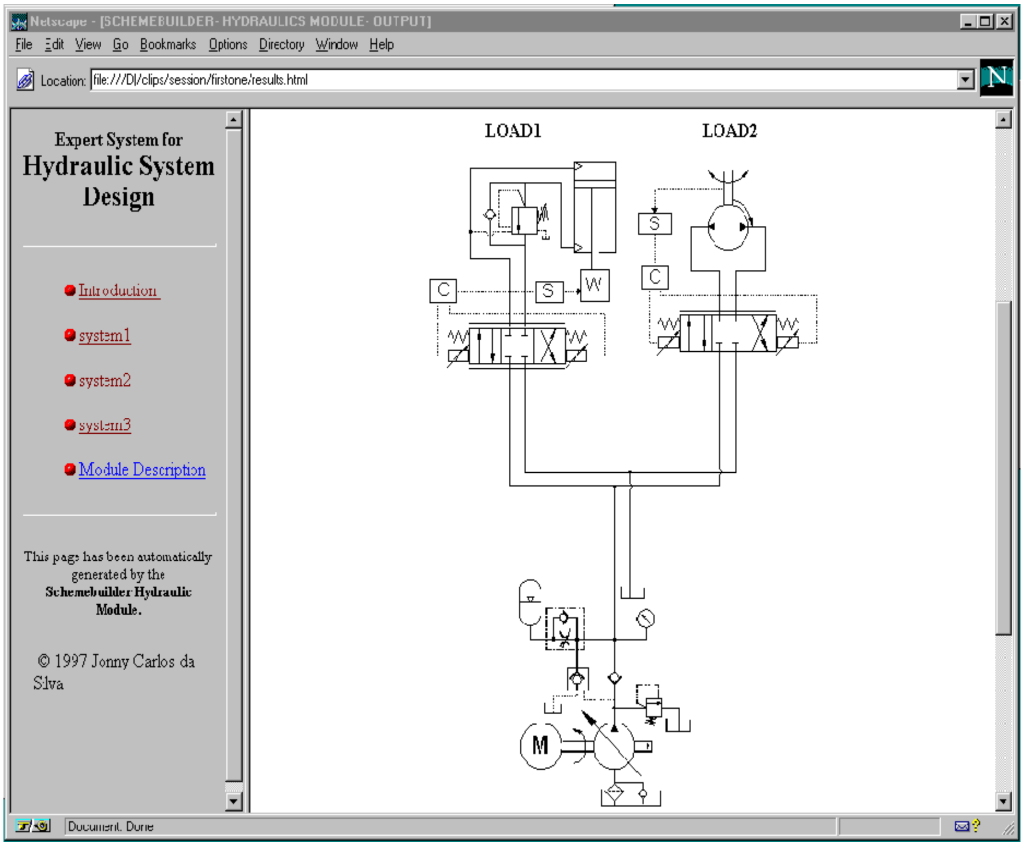

Figure 3. HTML output automatically created by the prototype.

Figure 3 shows one of the three functional solutions, represented by the links in the left window, generated by the prototype for a two-load machine. In this diagram, each block of components corresponds to a circuit object, i.e. the figure presents two actuation circuits and one power supply unit that compose the overall system. By way of textual and graphical representations, the user is allowed to navigate through the design solutions, analyzing the other systems or even their circuits, as he/she navigates on the WEB. Since the prototype automatically loads the browser, no knowledge of HTML is required.

Through this interface, the user can browse the circuit files, via hyperlinks. Each circuit file presents a diagram, a textual explanation (including circuit general description and why the option was chosen for a specific load) and a list of components. It should be mentioned that an explanation facility is considered a key expert system feature (Gonzalez,93).

As presented in the functionality list, the prototype offers a facility to change the power supply option, to size the circuits and rank the alternatives. Those facilities are carried via user friendly dialog boxes and the output is generated in HTML, thus there is an interaction between the user and the prototype, as shown in the next figure.

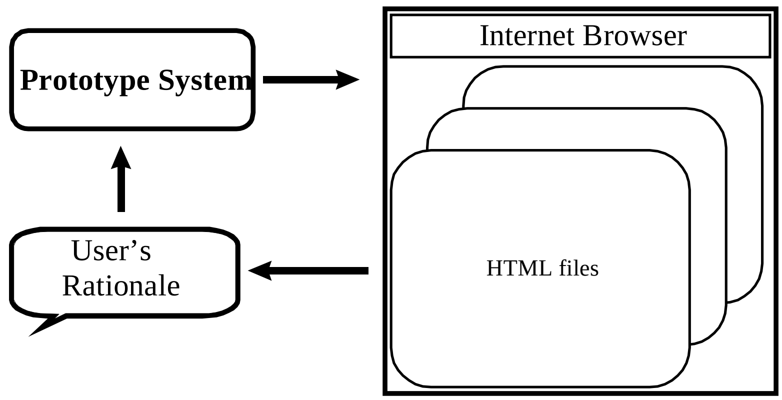

Figure 4- User, Prototype System and Internet Browser Interaction.

The interaction combines the user friendliness of an INTERNET display, the prototype capacity to promptly create, from specific knowledge on hydraulics, a semantic network among different objects (systems, circuits and components), generating a series of HTML files, and the user's ability to perform highly cognitive tasks, such as to compare functional solutions and make design decisions. Although this system is in its prototypical stage, its features clearly demonstrate an application of Artificial Intelligence to fluid power design (Silva,98c). Further aspects regarding the concurrent engineering perspective considered in the prototype structure, including power supply unit analysis/replacement, system ranking and quick circuit sizing, are presented in (Silva,98d). Next section discusses issues on knowledge representation and acquisition to support the prototype expansion.

4. KNOWLEDGE REPRESENTATION AND ACQUISITION

Concerning the issue about how the designers think, some researchers suggest that experts, in an area very close to hydraulic system, tend to think in terms of Conceptual Chunking (Cooke,92). They replicated the traditional expert-novice recall of results with electronics technicians and the reconstruction of symbolic circuit drawings. Results indicated that experts attempted to recall drawings (i.e., a drawing with random placement of circuit symbols) in terms of units that were functionally related. In addition, the experts were faster than the novices on between-chunk transitions and often characterized the entire display in a matter of seconds. Although Conceptual Chunking, as presented in the reference, was not applied directly in the developing system, it supports the concept of a circuit as a working principle and of a hydraulic system as a scheme (French,85).

Other research postulates that a world of design information consists of many different sized groupings. This can be modeled by an object-oriented technique which possesses the representational adequacy to create a model containing separate hierarchical representations for distinct empirical concerns in a product engineering domain. Thus, object-oriented software systems are advantageous for modeling engineering design activities because of their support for complex relationships and evolutionary processes (Zucker,92).

Further research on design area, near to the present work field, which supports the application of Object-Oriented techniques presents the following remarks (Yalif,94): The data used during airplane design can be very complicated. Each part of the plane, such as the engine, has its own specifications. Each part also contains subparts, just as the engine has a turbine, compressor, and fuel pumping system. Each of these subparts has its own specifications in addition to sub-subparts. Therefore, design data needs to be arranged in an ordered manner that is readily accessible and understandable to the user. Object Oriented Design (OOD) is useful for storing the complex, voluminous and hierarchically arranged data produced during airplane design. The conclusion: “The object-oriented data model was found to be a better data modeling method for modeling aerospace vehicle design process” than any of the others studied.

Based on these researches and the intense use of object-oriented properties, namely, abstraction, polymorphism and inheritance (Gonzalez,93), this project applied object-oriented modeling combined with rule-based paradigm as the core for knowledge representation (Silva,97a). This decision proved to be one the most important point to contribute to the prototype development. Next figure presents an overview of the class structure modeled in the prototype.

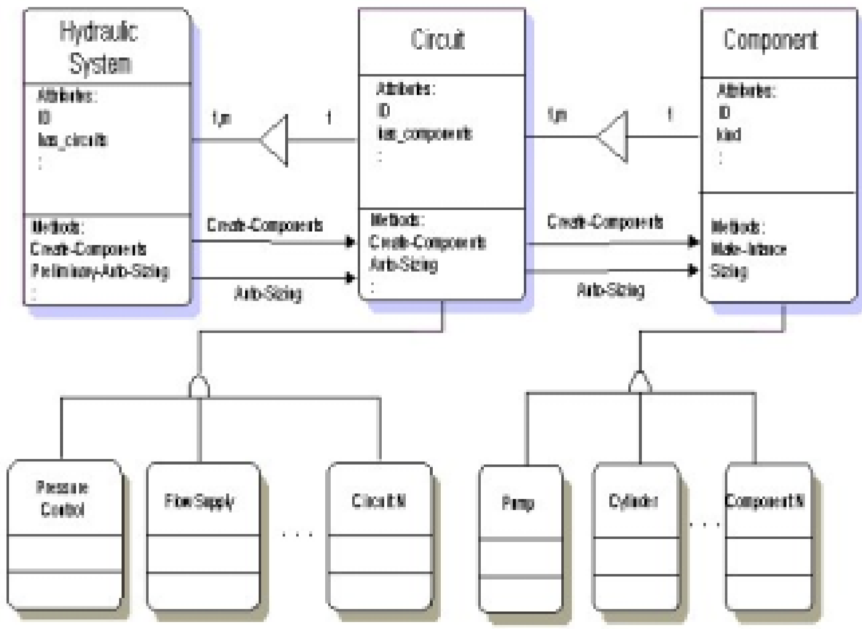

Figure 5. Inheritance and Assembly Relationships Among Classes.

Figure 5 shows the hierarchical relationships among system, circuit and component classes. With this modular structure, new types of hydraulic circuits can be modeled, and more attributes included (such maintenance and cost guidelines). Moreover new classes can be added, as demonstrated during the prototype development, since the *designer class* (not shown) was later included to model designer's basic attributes (e.g. email, company and name) keeping the same software structure. Such modular framework was vital to allow the system expandability (Silva,98b).

Besides the selection of proper knowledge representation techniques, it is vital, for a successful project, to choose an adequate development model. In this project, the incremental model was chosen. Basically, this model proposes that while some “parts of knowledge” are being acquired and formalized, others previously implemented are being validated. In this way, it is possible to coordinate the system development in an organic growth. The incremental model has been used very successfully in large conventional software projects. The incremental model is also useful for expert systems development in which the addition of rules increases the capabilities of the system from assistant, to colleague, and finally expert level. The primary advantage of this model is that the increases in functional capability are easy to test and validate. Each functional increment can be tested immediately with the expert rather than trying to do the entire validation at the end (Giarratano,94). Next section presents some aspects of on how the system will be expanded to embrace more cost consideration.

5. COST CONSIDERATION

In a computational environment aiming a concurrent engineering perspective, it is clear that cost should be given adequate attention. In the prototype, cost effectiveness was considered one of features in a comparative analysis among the design alternatives generated by the system (Silva,98d). Although this approach was accepted by the general public, i.e. expert and non-expert users or engineers, cost as a design attribute deserves a greater attention, for predicting the overall cost of a system in its conceptual design stage may prove to be an invaluable tool.

However, unlike guidelines regarding maintenance, in which most of information is available in public sources (text books and supplier catalogues), to implement a module for dealing with cost greatly depends upon the interaction between developer and knowledge sources, i.e. industries, system designers and component suppliers.

Although there has been interest from industrial agents throughout the prototype development, the knowledge engineer concludes that this interest does not necessarily mean that they had been keen to provide key information to the development, rather it manifests the prototype potential to enhance the design activity in an industrial environment.

Similarly to any computational system for industrial application, in the cost analysis module, it seems that either one industry directly demands this specific system or the knowledge engineer has to demonstrate, most likely through a workable prototype, the potential benefits of such tool to industries. Unless the knowledge engineer is able to convince at least one industrial partner to invest its experts' time, and possibly some financial support, to develop a cost analysis module, this endeavor may not be considered worth to embark in. In order to attract interest from the industrial sector the author assumes a proactive approach, namely to propose and illustrate the potential that such tool has to the fluid power community and raise the awareness of this market to application of Artificial Intelligence to real world problems (Lyons,98).

In the context of cost estimate, an expert system can be used to:

- Offer a ballpark of the overall cost of a hydraulic system based on heuristic knowledge gathered from different expert sources, mainly experienced designers.
- Calculate the cost of components, and estimate the assembly cost based on application area, pressure and power requirement, types of components and types of control strategies, i.e. valve or pump control.

Similarly to the prototype development, most of knowledge harvesting in this expansion will take place through posted questionnaires to key web sites and email messages to experts. The developer has experienced this approach, defining a clear knowledge acquisition process (Silva,97c), which also eases the validation and documentation stages.

In the present context, the objective is to acquire knowledge regarding cost estimate related to design hydraulic systems. Knowledge will be gathered from different sources (technical literature, designers' expertise, component manufacturers catalogue, internet posted questionnaires, etc.). Such information collected will be represented in an Artificial Intelligence tool to predict the cost of hydraulic systems from the conceptual design stage. Instead of developing a spreadsheet type system to precisely calculate the costs of components, given a certain design, in this project, the intention is to base the system on expert knowledge, formulated through rules of thumb, which most of times are presented in a fuzzy logic form. Therefore, the system expansion will map uncertainty as its main feature.

It is know that the overall cost of a hydraulic system must depend on factors such as: Power demand, types of actuation systems (different cylinders, and types of motors); types of valves (on-off, proportional or servo-valves), types of pumps and application area (requiring diverse degree of contamination control), etc.

The first step is to establish the cost structure of a hydraulic system, for without knowledge of the cost structure, designers cannot identify the measures that would lead to cost reduction (Pahl,96). In other to produce valuable results, specific application areas will be chosen, e.g. mobile or industrial, since the cost structure may considerably vary from each area. Once a cost structure is conceived, the prototype expansion takes place by adding attributes (and their values) for the components and/or corresponding circuits. The collected values will be used to reason through rules in other to provide guidelines to the designer, for example which is the best pump to select for a certain application.

6. CONCLUSION

Mainly in the cost area, the developer will need access to the organization records that may contain commercially sensitive information. Those records may also contain embarrassing information with respect to the client's past competence and its personnel. Thus the client organization may be reluctant to release what may be the most informative records and the developer must possess a considerable degree of tact when dealing with such cases. The developer will also need access to the current tasks that are possibly sensitive. Perhaps the major expense to the organization is the disruption that is likely to be caused to their current operations by the loss, even for limited period of time, of their expensive and valuable domain experts (Diaper,90). Thus, if a successful expert system is to be developed then the client organization must be a willing partner in the enterprise.

Definitely, this is a changeling project, for the idea is to create a module as useful tool, and at the same time, easy to operate, i.e. without demanding a great deal of expert knowledge in hydraulics from the user. Despite being a challenge, this project is based upon the author's experience of more than four years organizing, coding and validating knowledge directly related to hydraulic system design, whose result is a working prototype already demonstrated at several technical events and trade shows. At the present, the author is collecting advice from experts in response to some of the above mentioned messages.

Acknowledgements

The author thanks the Mech. Eng. Dept. of UFSC and CAPES Agency for their support during the project.

REFERENCES

Brazier,90. Brazier, D. and Leonard, M., "Concurrent Engineering Participating in Better Design", *Mechanical Engineering*, January, 1990, Vol. 112, No. 1, pp. 52-53.

Cooke,92- Cooke, Nancy J., *Modeling Human Expertise in Expert System*, The Psychology of Expertise, Cognitive Research and Empirical AI, edited by Robert R. Hoffman, Springer-Verlag, 1992, pp 29-60.

Diaper,90- Diaper, Dan. An Organizational Context for Expert System Design. Chapter 12- Expert Systems- Human Issues. Editors Dianne Berry and Anna Hart., Chapman and Hall, 1990.

Esposito,97. Esposito, Anthony 1997. *Fluid Power with Applications*, Prentice Hall, Inc.

French,85- French, M.J., *Conceptual Design for Engineers*, 2nd. Ed., Design Council, London, 1985.

Giarratano,94. Giarratano, Joseph and Riley, Gary 1994. *Expert Systems- Principles and Programming*, Second Edition, PWS Publishing Company, 1994.

Gonzalez,93. Gonzalez, Avelino J. and Dankel, Douglas D., *The Engineering of Knowledge-Based Systems- Theory and Practice*, Prentice-Hall, Inc., 1993.

Lyons, 98. Lyons, Danyel. Artificial Intelligence gets real. Forbes Magazine, Nov. 30, 1998.

Klement, Mary A. 1993. Design for Maintainability. *Concurrent Engineering: automation, tools and techniques*. Edited by Andrew Kusiak, John Wiley & Sons, Inc. 1993.

Pahl,96. Pahl, G. & Beitz, W.. Engineering Design: A Systematic Approach. Springer-Verlag

London Limited 1996.

Schneider,98. Schneider, R.T. and Hitchcox, A.L. 1998. Fluid Power Technology Shapes Industry Worldwide. *Hydraulics & Pneumatics Magazine,* Penton Publishing, March, 1998.

Silva,97a, Silva, Jonny C. and Cheung, H.F.. Computer Support Environment Applying Object-Oriented Methods for Hydraulic Systems Design, *Lancaster International Workshop on Engineering Design Computer Aided Conceptual Design*, CACD'97, *United Kingdom*, 14-15 April,1997.

Silva,97b, Silva, Jonny C. and Dawson, David. The development of an expert system for hydraulic systems design focusing on Concurrent Engineering Aspects. *ICED97 International Conference on Engineering Design*, Tampere, *Finland*, 19-21 August 97, Vol. 1, pp 271-276, ISBN 951-722-788-4.

Silva,97c, Silva, Jonny C. and Dawson, David. Knowledge Acquisition In The Context Of Hydraulic Systems Design- A Case Study. *Tenth Bath International Fluid Power Workshop*. University of Bath, *United Kingdom*, 10-12 September 97.

Silva,97d, Silva, Jonny C.; Bennett, David and Counsell, J. M. Computational Agent to Integrate Expert System and Simulation Language. *9th European Simulation Symposium*, Passau, *Germany*, October 19-23, 1997.

Silva,97e. Silva, Jonny C. and Dawson, David. Computational Agent to Integrate An Expert System for Design and The Internet. *WebNet97 World Conference of the WWW*, Internet and Intranet. Oct. 31-Nov. 5, 1997, Toronto, *Canada,* ISBN 1-880094-27-4.

Silva,98a. Silva, Jonny C. da. Expert System Prototype for Hydraulic System Design Focusing on Concurrent Engineering Aspects. Doctorate Thesis in Mechanical Engineering. Federal University of Santa Catarina, *Brazil*, March 1998.

Silva,98b. Silva, Jonny C. and Dawson, David. Expert System for Design-Validation and Expandability Issues. Lancaster International Workshop on Engineering Design. Computer Aided Conceptual Design CACD'98, *United Kingdom*, May 1998.

Silva,98c. Silva, Jonny C.. A Inteligência Artificial na obtenção de um sistema computacional para projeto de sistemas hidráulicos. Revista da Associação Brasileira de Hidráulica e Pneumática (ABHP) Artigo Técnico, pp 7-10, março/abril 1998.

Silva,98d. Silva, Jonny C.. Projeto de sistemas hidráulicos numa abordagem de engenharia simultânea. VI Seminário Nacional de Hidráulica e Pneumática, 22 a 25 setembro 1998, Minas Gerais, *Brasil*.

Silva,99. Silva, Jonny C.. Concurrent Engineering Perspective of Maintenance Aspects through an Expert System Prototype. Spring Symposium organized by the American Association for Artificial Intelligence. *Stanford University*, California, USA, March 22-24, 1999.

Yalif,94. Yalif, Guy U.. *The Computer Aided Aircraft-Design Package CAAP*, Third Conference on CLIPS, Proceedings Electronic Version, September 12–14, 1994, Lyndon B. Johnson Space Center.

Zucker,92. Zucker, J. & Demaid, A.. *Modelling Heterogeneous Engineering Knowledge As Transactions Between Delegating Objects*, Artificial Intelligence In Design'92, Sydney, Australia, pp. 141-149.