PUC

ISSN 0103-9741

Monografias em Ciência da Computação
nº 09/94

Making a Case for Design Rationale in the A/E/C Industry

Jesus M. de la Garza
Ana Cristina Bicharra Garcia
H. Craig Howard

Departamento de Informática

PONTIFÍCIA UNIVERSIDADE CATÓLICA DO RIO DE JANEIRO
RUA MARQUÊS DE SÃO VICENTE, 225 - CEP 22453-900
RIO DE JANEIRO - BRASIL

PUC RIO - DEPARTAMENTO DE INFORMÁTICA ISSN 0103-9741

Monografias em Ciência da Computação, Nº 09/94
Editor: Carlos J. P. Lucena July, 1994

Making the Case for Design Rationale in the A/E/C Industry*

Jesus M. de la Garza**
Ana Cristina Bicharra Garcia
H. Craig Howard***

---

* This work has been sponsored by the Ministério de Ciência e Tecnologia da Presidência da República Federativa do Brasil.

** Virginia Tech, Department of Civil Engineering, 200 Patton Hall, Blacksburg, VA, USA

*** Department of Civil Engineering, Stanford University, Stanford, CA, USA

In charge of publications:
Rosane Teles Lins Castilho
Assessoria de Biblioteca, Documentação e Informação
PUC Rio — Departamento de Informática
Rua Marquês de São Vicente, 225 — Gávea
22453-900 — Rio de Janeiro, RJ
Brasil
Tel. +55-21-529 9386 Telex +55-21-31048 Fax +55-21-511 5645
E-mail: rosane@inf.puc-rio.br

Making a Case for Design Rationale in the A/E/C Industry

by

Jesus M. de la Garza, Ana Cristina Bicharra-Garcia, and H. Craig Howard

Working Paper—March 1994

Author: Jesus M. de la Garza
Address: Virginia Tech
Department of Civil Engineering
200 Patton Hall
Blacksburg, Virginia
United States of America
Phone: (703) 231-5789
Fax: (703) 231-7532
E-mail: chema@vtvm1.cc.vt.edu

Author: Ana Cristina Bicharra-Garcia
Address: Pontificia Universidade Católica-PUC-Rio
Rua Marquês de São Vicente, 225
Rio de Janeiro
Brazil
Phone:
Fax: +55 21 5115645
E-mail: bicharra@inf.puc-rio.br

Author: H. Craig Howard
Address: Department of Civil Engineering
Stanford University
Stanford, CA 94305-4020
USA
Phone: (415) 723-5678
Fax: (415) 725-8662
E-mail: hch@cive.stanford.edu

ABSTRACT

Articulation and use of design rationale are critical elements in improving design, construction, and facility management in the architecture/engineering/construction (A/E/C) industry. This paper summarizes some of the research work on design rationale in the fields of construction and software engineering, and shows how design rationale could be captured and employed in the A/E/C industry. The articulation of design rationale should be a standard activity in the entire design process starting with owner's initial conception of the facility, the designer's elaborations on that concept, construction by the contractor, and finally, operation by the facility's managers. Owners of constructed facilities need to recognize the usefulness of this new design output product called "design rationale" as a valuable addition to the typical construction documents already produced, i.e., drawings, specifications, and as-builts. We argue that design rationale, if adopted as a valid concept, can be articulated and used through software tools and that these need to be embedded within the key software packages that designers are already using.

INTRODUCTION

The development of a constructed facility requires the collaboration and coordination of many specialists with different backgrounds. Such development, i.e., the facility's life-cycle, evolves from a nebulous idea of needs and requirements, to detailed design, to construction, to operation and maintenance, to renewal, and eventually, to decommissioning. Design decisions are time-dependent and are the result of skillful negotiations among the many life-cycle participants.

Input sources to the life-cycle of a facility are aligned with the corresponding horizontal and vertical fragmentation prevailing within the US A/E/C industry [Howard et al. 1989]. Figure 1 shows that input can come from multiple A/E/C players at a given life-cycle development stage (horizontal fragmentation) and that a single player is not involved in all life-cycle phases (vertical fragmentation).

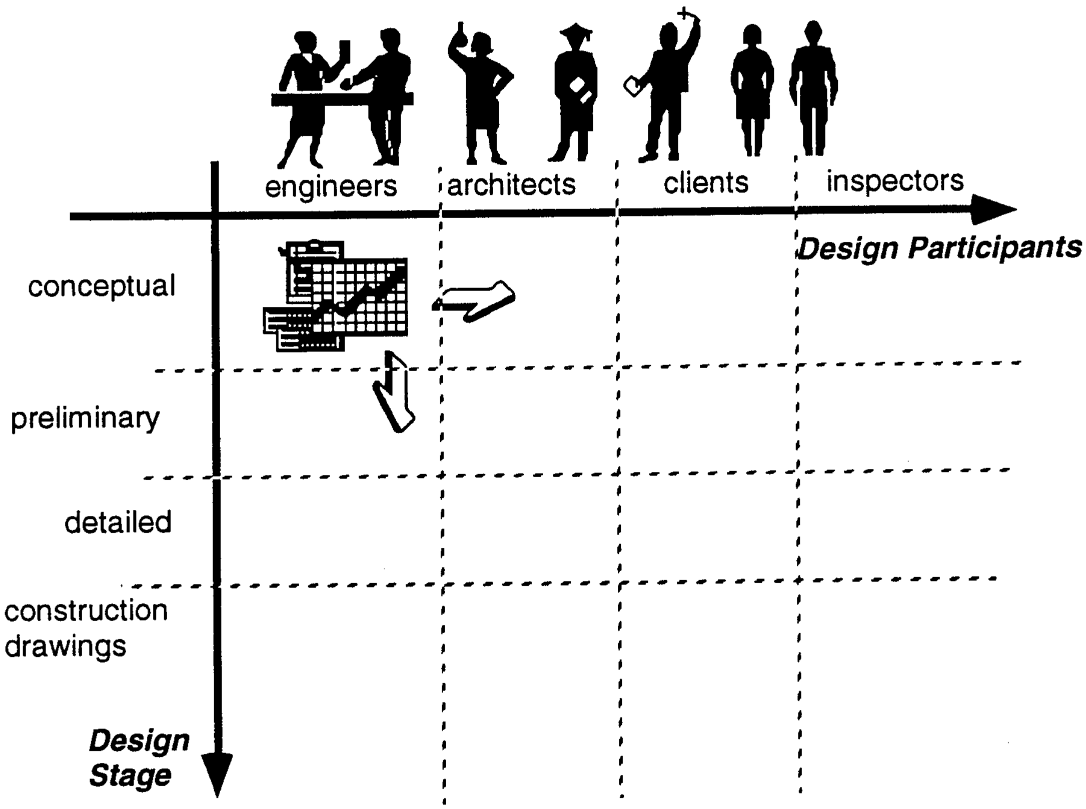

Figure No. 1 Communication Needs throughout a Facility's Life-Cycle

It is common practice for each A/E/C player to contribute to the life-cycle development in a way that best satisfies individual goals (local optimization). In addition to fostering localized innovation and efficiencies, owners of constructed facilities need to ensure that decisions taken in the upstream stages are evaluated relative to their impact on downstream life-cycle phases (global optimization). For example, in a building design, the best architectural design may lack constructability or lead to a poor energy conservation system during the building's operation.

Even though there are many interactions between life-cycle phases, they can be considered chronologically sequential. As Coyne states, design evolves until becomes reality [Coyne et al. 1990]. Each life-cycle stage produces documents that address different issues. During the conceptual design phase, the design team develops the building's concepts and requirements.

In the preliminary design phase, each design trade develops a set of alternatives that satisfy the set of design requirements. After negotiation with other design participants, the design is detailed. The detailed design is further specified to include construction instructions. If one considers construction as a child subprocess of design, then the design is finalized when the actual construction of the facility comes to an end.

Traditionally, only the product distilled from the design decision-making process is made explicitly available. Examples of these products include: sketches and performance requirements transmitted from the client to the designer; paper plans and specifications literally "thrown over the wall" by the designer to the contractor; and as-built drawings transmitted from the contractor back to the client. The corresponding implicit decision-making processes related to these products include, among other things: the motivation and objectives for the facility, the client and user requirements, the client and user preferences, the functional requirements, the mapping of functional specifications to performance requirements, the mapping of performance requirements to physical properties of building components, the justification for design alternatives, the justification for design choices, deliberations about trade-offs, the justification for as-built deviations from the design, etc. The need to disseminate both:

- the decision-making process; and
- the products of such decision-making process

has long been identified. However, until very recently the focus has been on the latter. The search for a better competitive edge, the technological advances and the scarce budgets have guided researchers to look toward improving the understanding of the design process. It is within this context that design rationale research area takes place. Six fundamental questions direct researches in this area:

- How to define rationale?
- How to acquire rationale efficiently?
- How to represent rationale for computer processing?
- How to retrieve rationale efficiently?
- How to make intelligent inferences from rationale?
- How to measure the impact of having access to design rationale on a project's life-cycle?

Design is an inherent idiosyncrasy of human beings. We design all kinds of artifacts, ranging from concrete entities like buildings and cars to abstract concepts like computer programs and experiments. Design rationale is thus a generic concept that has found applicability in multiple disciplines. Among the unresolved issues is whether there is a single representation formalism for design rationale or whether it is discipline-dependent. Another pragmatic issue is to determine the intended consumer for design rationale. If one targets humans, then one can rely on textual explanations because presumably everyone can read, write, and comprehend them. However, if one wishes to have computers represent and reason with design rationale, one needs to have rigorous representation and reasoning formalisms. This is analogous to representing and reasoning with human expert knowledge. For this, one can employ knowledge-based expert system shells, which provide the developer with rigorous representation formalisms such as rules, frames, and methods, and with formal reasoning strategies such as forward chaining, backward chaining, inheritance, and message-passing.

The objective of this paper is to make a case for legitimizing the articulation and use of design rationale within the A/E/C industry. In doing so, we argue that a better understanding of a facility's life-cycle process will be achieved, thus enhancing the possibility to produce a product, i.e., a constructed facility, of the highest quality. In this paper we use the term design rationale to include everything from the owner's intent, to the designer's intent, and the contractor's as-built intent. When we refer to the refined knowledge of a specific party, we use the term intent.

CONCEPTUAL UNDERPINNINGS

Design rationale can be thought of as a collection of interrelated justifications and assertions that fuel an explanation engine responding to "what", "why", "why not", "what if", "how", "when", "who", and "where" questions about a facility being conceived, designed, built, and operated. Design rationale can be, for example, a client requirement or preference, a functional characteristic, a performance criterion, a constructability matter, or a designer's philosophy that plays a major role in the design, dimensioning, material selection, construction, and operation of a building, a space, or a building element. Design rationale is usually trapped in the minds and personal notes of the individuals charged with decision-making, and, as a consequence, it tends to be private and not necessarily reproducible upon demand. Design rationale encompasses the record of the historical design decision-making process as well as search space of plausible design alternatives.

As it was indicated earlier, constructed facilities have a life-cycle. It begins upstream with project conception and ends downstream with project decommissioning. In between there is design, procurement, operation, maintenance, rehabilitation, and retrofit. Design rationale has a shadowing effect on all life-cycle phases that follow the one in which it is created. Therefore, the owner's intent, if articulated and made explicit, benefits the designer, builder, and the end-user of the facility. Similarly, the designer's intent, if articulated and made explicit, benefits the builder and end user of the facility. Finally, the contractor's as-built intent is of value to the end user of the facility. It follows that the design rationale of one project can serve as a building block for future projects.

If made explicit, design intent can leverage construction tasks and eventually the final product, via a better understanding of a project's function, performance and quality. Reasons given for generating explicitly design rationale include, among others, [Carroll and Moran 1991, MacLean et al. 1991, Conklin and Yakemovic 1991]:

- Further the accumulation and development of design knowledge across projects;
- Support both the original process of design or subsequent work on redesign by providing explicit reasoning about the consequences of changes to it;
- Serve as a vehicle for communication among original members of the design team and future builders, users, and maintainers of the facility;
- Provide a creation tool by forcing designers to think through the process in a disciplined, structured, and systematic way;
- Serve as a management tool to track changes and detect design errors;
- Brief new personnel in turnover situations;
- Retain and build organizational memory;
- Augmentation of the designer's memory;
- Preserve the intent of the standards.

The following examples show applications of design intent in construction:

- Design intent can improve the quality of specifications and guide the contractor's material selection when faced with a proprietary "brand-name or equal" specification [De La Garza and Oralkan 1994]. Proprietary "brand-name or equal" specifications allow designers to specify a given brand of material or equipment, but at the same time permit contractors to substitute the proposed brand with an equivalent one [Ibbs 1985];
- Design intent can also improve the contractor's understanding of design, hence increasing the compatibility of shop-drawings with the actual design and design philosophy. Shop drawing preparation, whose goal is to specify exactly and precisely how the project is put together, involves detailed designing by contractors based on their understanding of the project, via design drawings and specifications;
- Design intent can also aid the value engineer or the contractor who is preparing a value engineering proposal to solicit a second design which might cost less than the original design, but which is still at the same level of quality and value [De La Garza and Alcantara 1993].

ILLUSTRATING THE PROBLEM

We illustrate the documentation/rationale problem using some material from Garcia's empirical studies in the Heating, Ventilation and Air Conditioning (HVAC) design. Although the scenario is real, we have changed the names of the design participants and companies.

A large medium size HVAC design firm is developing a project for a commercial 5-story building located in San Jose, California. This company received an initial document from the architects containing the conceptual architectural project and a set of requirements to be considered. The HVAC system designers produced a preliminary design draft and sent to the architectural companies. This HVAC system preliminary design was analyzed by many other design participants.

As usual, there were many misunderstandings and disagreements appeared over the design among the design participants. In formal and informal dialogues, three types of questions were identified:

1) questions that triggered an information retrieval.
2) questions that investigated the consistency of the design (why x, if z)
3) questions that triggered an new design reasoning about the design (why-not and what-if questions);

Table 1 illustrates some questions that were sent to the HVAC system designers.

Type of question	Examples
1-(What, How, Where)	• Clarify the type of occupancy rating of the building (B2, etc.) • Is air quality a problem?
2-(Why)	• Why are you using 15 air changes per hour? Has it been calculated? (12 is fairly normal) • Why are we installing space fan carbon filterization?

3-(Why Not, What If)	• The mechanical rooms are scattered and will be difficult to maintain. Try to consolidate if possible. • *Why* did you use a central system *instead of* floor by floor system? • *What would be the impact* on the HVAC system design if we eliminate the first cost requirement?

Table 1: Examples of types of questions over a design

If the designer spends time carefully documenting his or her design, certainly the what-is-the-value-of questions can be answered by looking at the design documents. However, the why-is-the-value-of-x and why-the-value-of-x-not-equal-to questions can seldom be answered by looking at the documents. The what-would-be-the-impact type of question never can be answered, since the document is a static view of the design at a particular time.

These types of questions are very common in any design domain. The availability of an answer, the adequacy of the answer, and the consistency of the answer will depend on the quality of the document. Current paper documents provide little assistance to documentation users in understanding a design. Much research has been conducted on how to assist designers in capturing and retrieving the design rationale to improve the quality of the design process.

WORK ON DESIGN RATIONALE

Design rationale has been identified as a viable area of research by software engineers because the development of computer and information systems has become increasingly complex, because there exist higher demands for reliability, and because sophisticated computer systems are difficult to maintain [Conklin and Yakemovic 1991, Carroll and Moran 1991, MacLean et al. 1991, Lee and Lai 1991]. In the construction industry there have been already some attempts to understand design rationale. These efforts have aimed at developing domain-dependent models of representation and reasoning [Coyne at al. 1990, Ganeshan et al. 1991, Howard 1991, Kim 1987, Oralkan 1991, De La Garza 1992, Songer et al. 1991, Garcia and Howard 1992, Fischer et al. 1991]. The work of De La Garza and Oralkan focuses on interpreting "brand-name or equal" construction specifications for selecting building component materials or recommending substitute ones; the work by Garcia and Howard focuses on building domain-dependent models of design processes like the one used for designing HVAC systems; the work of Songer focuses on interpreting the conditions of a project and recommending its suitability for design-build contract; the work of Coyne and Kim focuses on architectural design and on interpretation of design specifications; and the work of Fischer et al. focuses on design by composition and modification in the domain of residential kitchen design.

Much of the work on design rationale has its roots on the Issue-Based Information System (IBIS) developed by H. Rittel and M. Webber [Carroll and Moran 1991]. The IBIS methods capture the issues, alternatives, and arguments that are brought about during the design decision-making process. In this way, the design decisions taken today can be re-analyzed in the future, thus fostering proper reconsideration and thought.

Other researchers [MacLean et al. 1991, Conklin and Yakemovic 1991] argue that a way to understand an artifact is to compare it with plausible alternatives. The QOC (Questions, Options, Criteria) approach "elicits" the design space of plausible alternatives, thus treating design rationale as a co-product of design in contrast to IBIS-derived systems whose purpose is to "capture" the history of design deliberations. The design search space by necessity includes the path between the initial state of no decisions made and the final state where all decisions have been made.

While the IBIS and QOC approaches represent design rationale with hypertext technology for human consumption, other design rationale researchers [Lee and Lai 1991, Klein 1993] have postulated that to offset the costs of producing design rationale, it needs to be computer processable, thus they have developed data structures (e.g., DRL and DRCS) to represent design rationale in such a way that computer inferences can be made as well. Some data structures are optimized to represent a single facet of design rationale. For example, representing the function of an artifact will account for a fair share of what is considered to be design rationale [Chandrasekaran et al. 1993].

History-based rationale models represent rationale as a sequence of events that take place during design. According to this approach, the "design log" is sufficiently rich to reconstruct the design and, consequently, to explain it. Many systems, such as Lakin's electronic notebook project [Lakin et al., 1989] and EDN [Karinthi, 1992], aim to provide an environment that can construct the design log. In this model documentation should contain all information and actions that take place during the design.

The device-model approach is based on many of the techniques and assumptions of device-model based expert systems, especially those for diagnosis. The basic motivation for that work is to provide more automatic methods for reasoning about a design by using detailed knowledge about the devices that comprise it. In this research branch, exemplified in work by Baudin [Baudin et al., 1989], a deep model containing form, function and behavior information about domain concepts supports the acquisition of rationale in a specific domain. One of the reasons this approach fails to document preliminary design is the use of an incomplete model. What needs to be modeled is not only the device, but also the design decision-making process leading to a device.

This approach has been more successful for diagnosis than for design. The reason is that in diagnosis the model for the system (composed of the modeled device) is more or less considered to be complete. However, in design, the system is unspecified. Indeed, the work of design necessarily involves exploration of the space of possible designs. This brings requirements for modeling specifications, tradeoffs, and social aspects of the design such as an analysis of the different needs of different documentation users. By their nature, device models do not make use of this information, and therein lies the source of their weakness.

The design-model approach is based on both domain and decision-making models as rationale. The existence of both models allows an active role for acquiring and retrieving rationale. ADD [Garcia 1992] is an example of an active tool for acquiring and generating rationale for the domain of preliminary Heating, Ventilation and Air Conditioning systems.

ADD's model for documentation integrates the mechanism for generating and explaining designs. ADD's documentation model leads to an initial design model for generating design explanations. Design rationale is elicited as modifications to ADD's initial design model. The adjusted design model represents the dynamic document able to generate explanations for a design reflecting a designer's design process. In addition to guaranteeing a consistent document that explains a design, the existence of the design model allows documentation users to further explore the design space. Consequently, besides revealing the assumptions considered during the design (one-way communication), the document allows the user to investigate the impact on the design caused by some changes in the specification considering this virtual designer represented by ADD's adjusted design model (two-way communication). In summary, ADD's documentation model offers a new approach that suits the communication requirements of preliminary routine design.

Approaches to acquiring and generating design rationale vary from passive to active, general expressiveness to domain-dependent, and low to high overhead [Garcia and Howard 1992, Conklin and Yakemovic 1991]. Table 2 presents some design rationale systems classified according to generality, overhead, and level of activity.

	Specific		**General**	
	High Overhead	**Low Overhead**	**High Overhead**	**Low Overhead**
Passive	mSybil [Ruecker and Seering 1992]		gIBIS [Concklin, 1989] SYBIL [Lee 1990]	NoteBook [Lakin, Wambaugh et al. 1989] EDB [Karinthi 1992]
Active	JANUS [Fischer, Lemke et al. 1991] SOS [De La Garza 1992]	ADD [Garcia and Howard 1992]	Device Models [Baudin, Sivard et al. 1989]	***Ideal***

Table 2: Design Rationale Systems

NEXT STEPS

Several key steps remain in the development of design rationale as a legitimate and critical part of the everyday design process. There are a number of critical technological issues, but there are economic and legal issues as well.

- **Standardization of underlying data models** — A critical part of tying design rationale to existing computer tools and to exchanging that rationale between designers is the underlying data model for the artifacts being designed. Ongoing efforts toward international standards for data exchange (e.g., STEP) are establishing a basis for the necessary data representations.

- **Standardization of rationale models** — Exchanging and combining rationale as it passes through the stages of a project will require some standardization of the rationale representation including standard elements such as alternatives, constraints, evaluation criteria, design agents, design contexts, goals, tasks, previous cases, etc. [Garcia 1992].

- **Integration of rationale capture with existing design tasks** — Industry professionals have repeated said that designers don't want to turn away from their design tasks to write explanations. We couldn't agree more. The act of rationale capture should be tightly integrated with the design task—in fact, the design environment should make it easy to infer the design rationale directly from the actions of the designer. Prototype systems like ADD provide a basis for the underlying reasoning to make that automated rationale capture possible. However, there is much work to be done on the design user interface issues.

- **Economic incentives for design rationale collection** — It is possible to make rationale capture a low cost activity, but generally knowledge capture will impose some overhead on the originators. While there are some benefits of this knowledge to the rationale originators (e.g., redesign and reuse in other designs), much of the value of the rationale is passed to the other design participants. Innovative contract mechanisms need to be devised to create economic incentives to the document the rationale as adequate as the physical characteristics of the design. Owners will probably be the catalysts in this pursuit since most of the end benefits in improved facilities fall to them.

- **Establishment of legal responsibilities with respect to rationale** —

More information on the designer's reasoning process will illuminate bad reasoning as well as good reasoning, potentially opening designer's to increased liability. However, at some future point there will be a transition to a professional climate in which a designer's lack of justification in the form of captured design rationale will be considered a breach of practice.

FINAL DISCUSSION

We have transitioned from an industry of master builders to an industry of specialists. Many pieces of the construction industry became extremely efficient, but consequently very fragmented. The benefits of specialization have long been evidenced in the localized optimization of design functions, construction operation, facility operation and maintenance processes, while the overall process has suffered from the fragmentation that has minimized productivity gains.

Designers are bound to experience gaps, misunderstandings, erroneous assumptions, which inevitably lead to costly re-work, schedule overruns, and compromised quality. Today's construction projects exhibit these three symptoms more often than we would like to admit. Hence, the rapid adoption of techniques like Total Quality Management by the construction industry should not come as a surprise.

More recently, the construction industry has also witnessed a revolution of sorts. Centralized mainframe computing power has been transformed into decentralized desktop computing through the proliferation of personal computers, engineering workstations, and powerful software development environments. For some key players of the construction industry, the advent of desktop computing has meant a unique opportunity to empower their workforce and to leverage their decision-making process, hence enhancing the quality of their corresponding products. For example, designers have embraced computer-aided design technology to produce better, more innovative and faster designs; contractors have been using estimating, scheduling and project management software to reduce inherent construction risks and thus, becoming more competitive; owners have been using facility management software to support their mission execution.

The time is ripe for the development of methods to integrate design rationale acquisition in the rapidly evolving facility engineering process. Tools that elicit and apply design rationale need to be closely integrated with traditional design tools so as to minimize the costs and maximize the payoffs as well as avoid disrupting the creative and reflecting design processes.

REFERENCES

Baudin, C., Sivard, C., et al. (1989). "A Model-based Approach to Design Rationale Conservation." *IJCAI 89*, Workshop on Model-based Reasoning, Detroit, Michigan.

Carroll, J.M. and Moran, T.P. (1991). "Introduction to This Special Issue on Design Rationale." *Human-Computer Interaction*, 6(3-4), pp. 197-200.

Chandrasekaran, B., Goel, A.K., and Iwasaki, Y. (1993). "Functional Representation as Design Rationale." *Computer*, IEEE, 26(1), pp. 48-56.

Conklin, E.J. and Begeman, M.L. (1989). "gIBIS: A Tool for all Reasons." *Journal of the American Society for Information Science*, 40, pp. 200-213.

Conklin, E.J. and Yakemovic, K.B. (1991). "A Process-oriented Approach to Design Rationale." *Human-Computer Interaction,* 6(3-4), pp. 357-391.

Coyne, R.D., Roseman, M.A., Radford, A.D., Balachandran, M., Gero, J. S. (1990). *Knowledge-Based Design Systems*, Addison Wesley Publishing Co.

De La Garza, J.M., and Oralkan, G.A. (1992). "An Object Space Framework for Design/Construction Integration." *Building and Environment: The International Journal of Building Science and its Applications,* 27(2), 243-255.

De La Garza, J.M., and Oralkan, G.A. (1994). "Using Design Process Knowledge for Interpreting Brand Name or Equal Specifications." *ASCE Journal of Computing in Civil Engineering*, forthcoming.

De La Garza, J.M., and Alcantara, P. (1993). "Applications of Design Intent in Value Engineering." *Applications of Artificial Intelligence in Engineering VIII,* Vol. 1, Computational Mechanics Publications, July, 1993, pp. 219-231.

Fischer, G., Lemke, A.C., McCall, R., and Morch, A.I. (1991). "Making Argumentation Serve Design." *Human-Computer Interaction*, 6(3-4), pp. 393-419.

Ganeshan, R., Finger, S., Garrett, J.H. (1991). "Representing and Reasoning with Design Intent." *Proceedings of the First International Conference on Artificial Intelligence in Design*, Edinburgh, United Kingdom.

Garcia, A.C.B. and Howard, H.C. (1992). "Acquiring Design Knowledge Through Design Decision Justification." *Artificial Intelligence in Engineering Design and Manufacturing*, 6(1), pp. 1-13.

Howard, H.C., Levitt, R.E., Paulson, B.C., Pohl, J.G., Tatum, C.B. (1989). "Computer Integration: Reducing Fragmentation in AEC Industry." *Journal of Computing in Civil Engineering*, ASCE, 3(1), pp. 18-32.

Howard, H.C. (1991). "Project-Specific Knowledge Bases in AEC Industry." *Journal of Computing in Civil Engineering*, ASCE, 5(1), pp. 25-41.

Ibbs, C.W. (1985). "Product Specification Practices and Problems." *Journal of Construction Engineering and Management*, ASCE, 111(2), pp. 157-172.

Kim, M.K. (1987). "Development of Machine Intelligence for Inference of Design Intent Implicit in Design Specifications." *Computability of Design*, ed. Y. E. Kalay, Wiley.

Karinthi, R. (1992). "Capturing Design Rationale for Use in a Concurrent Engineering Environment." *AAAI 92*, Design Rationale Workshop, San Jose, California.

Klein, M. (1993). "Capturing Design Rationale in Concurrent Engineering Teams." *Computer*, IEEE, 26(1), pp. 39-47.

Lakin, F., Wambaugh, H., et al. (1989). "The Electronic Design Notebook: Performing Medium and Processing Medium." *Visual Computer: International Journal of Computer Graphics*, 5(4), pp. 214-226.

Lee, J. (1990). "SIBYL: A Qualitative Decision Management System." *Artificial Intelligence at MIT: Expanding Frontiers*, MIT Press.

Lee, J. and Lai, K.Y. (1991). "What's in Design Rationale?." *Human-Computer Interaction*, 6(3-4), pp. 251-280.

MacLean, A., Young, R.M., Bellotti, V.M.E., and Moran, T.P. (1991). "Questions, Options, and Criteria: Elements of Design Space Analysis, *Human-Computer Interaction*, 6(3-4), pp. 201-250.

Oralkan, G.A. (1991). "An Object-Oriented Design Intent Externalization and Representation Model for Cost Estimating Applications." *Master of Science in Civil Engineering Thesis,* Virginia Tech, December.

Ruecker, L., and Seering W. P.(1992). "Extending Semi-Formal Design Rationale Systems." Proceedings of the AAAI'92, Design Rationale Capture and Use Workshop, San Jose, CA, pp. 235-252.

Songer, A.D., Ibbs, C.W., and Garrett, J.H. (1991). "Modeling Intent in DB Advisor." *Proceedings of the Seventh Conference on Computing in Civil Engineering*, ASCE, Washington D.C., pp. 54-63.