# The information requests of mechanical design engineers

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*Design documentation does not typically include all of the information sought by mechanical design engineers. This paper reports on a study of practicing engineers making modifications to existing designs. Particular attention is paid to the design information required to answer questions about the design and to verify and refute conjectures about the design. A taxonomy of the questions asked by the designers in this study and the conjectures they formed is presented. It is proposed that an intelligent CAD system be developed to capture, structure, and re-play this information.*

*Keywords: mechanical design, design documentation, CAD*

Current design documentation consists of a complete set of blueprints, showing the physical structure of a design, along with specifications, showing the manufacturing process. Designers are encouraged to keep design notebooks as well. These are often maintained along with the more formal documentation. A design notebook is traditionally a bound notebook in which all of a mechanical engineer's work on a particular design is performed and recorded. The *ideal* design notebook contains every written or drawn artifact relating to a design, from concept to blueprint. The pages in such notebooks are permanently bound, numbered, and dated.

With a clear and comprehensive design notebook, one could follow the progression of a design from the original germ of an idea through its various iterations to the final, completed design. Design notebooks are held to be useful, even essential, during the initial design process (to record decisions) as well as in cases of patent law (claiming the originality of a design), liability litigation (proving the validity of a decision making process), and in subsequent design efforts. Subsequent efforts could include modification to the original design, using the original design as a model when designing a similar object, designing an adjacent component as in an assembly, or analysis of the design by management or in downstream efforts such as drafting or manufacturing.[1–3]

The problem with the current state of design notebooks is that very few (possibly none) are maintained to the above ideal of completeness. Sketches are made on cocktail napkins and the backs of envelopes, groups work out ideas on chalkboards, realizations are made in the shower and on the way to work, decisions are made on the shop floor in response to unforseen conflicts or opportunities. This work seldom makes it into even the most meticulous of design notebooks. Additionally, notes that make perfect sense to the original designer when written may be unintelligible to any other person and jumbled even to the original designer months later.

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An intelligent computer aided design (CAD) tool could potentially maintain design notebooks automatically. Having a computer tool maintain the design notebook has the advantages of automatically capturing complete design information and structuring this information in a useful manner.

This intelligent CAD system should contain the information about a design that human designers are interested in. It should have a knowledge base capable of answering questions a designer might post about a design and verify or refute any likely conjecture about the design.

This paper reports on research performed to identify the design information designers are interested in, the questions designers ask which could be answered by intelligent CAD and the assumptions designers make that could be verified by intelligent CAD. Research is on-going to determine a format to store and replay this information and to determine a method of capturing it.

## RESEARCH METHODS

Three professional mechanical design engineers were used as subjects in the research. The subjects were given a complete set of blueprints and original specifications for completed designs and were audio- and video-taped while making modifications to these designs. Experiments of this sort are known as question asking protocols.[4–8] As they worked, each subject sought certain information about the design. Much of this information was available in the documentation provided. To supplement the documentation, an examiner who was familiar with the designs was available as a design information resource. Any inquiry for design information was labelled a question and examined carefully in the analysis of these protocols.

Also of interest were the conjectures formed by the subjects. Conjectures are formed when a designer does not have enough information to know things with certainty but can make an informed guess. The information necessary to verify uncertain conjectures was also analysed in this study.

The three protocols ranged in length from just over 1 h to 2 h 45 min. S10 was the first subject, the protocol being performed in February 1988. The re-design protocol problem for this subject was based on the design of a piece of manufacturing equipment that dips aluminium plates into a water bath coating them with a thin chemical layer. The original design was performed during a separate 6 h video-taped protocol. (For complete specifications of the designs, see Stauffer[9] or Kuffner[10]) S10 was given blueprints of the finished design, the original specifications, and four proposed changes to these specifications. The S10 protocol was studied in some depth and the protocol technique refined before continuing with the S11 and S12 protocols in June 1989.

The S11 protocol was based on the same design as the S10 protocol. To streamline the process, however, S11 was given only two changes to make.

S12 worked on a different design: a plastic enclosure for three small batteries and the formed copper contacts for connecting these batteries in series. This was designed by yet a different protocol subject in a 12 h protocol. As with the other subjects, S12 was given finished blueprints and the original problem specifications for this design and was given two changes to make to the design. A different design was chosen for S12 in an attempt to acquire more general results than would be obtained if all subjects worked on the same design.

The S11 and S12 protocols differed from the S10 protocol in one important aspect. All three protocols were preceded by a brief warm-up session. This acted as an equipment check and got the subjects accustomed to the verbal protocol process. S10 warmed-up by performing a simple original design problem without any examiner intervention. The warm-up sessions for S11 and S12 involved re-design tasks that were similar to those they worked on during the actual re-design protocols. In these sessions, however, instead of only answering direct questions about the design, the examiner worked with the subjects by volunteering design information thought to be helpful. The examiner thus tried to build a rapport with the subjects and worked to train the subjects as to how stored design information could be used as a re-design tool. This different approach resulted in the two later subjects asking more questions than S10. S11 used the examiner's knowledge 2.3 times more than S10 and S12 used the examiner's knowledge 3.5 times more than S10 to answer questions and verify conjectures. The other functions of the warm-up session, to ensure that the equipment was functioning properly and to make the subjects feel more comfortable verbalizing their thoughts while working, were also achieved by this procedure.

## ANALYSIS TECHNIQUES

The analysis of the protocols focused on the questions that the subjects asked and the conjectures that the subjects formed, the hypothesis being that access to a complete design information would answer all questions and eliminate the need for unsupported conjecture. The following definitions are used in this research:

*Question:* Interrogation by the subject or discussion initiated by the subject about any uncertain aspect of the design. These inquiries may be directed toward either the examiner, the designer's notes, drawings, given specifications, or the subject's own memory.

*Conjecture:* Conclusion about the design inferred by the subject from incomplete information. Interpretation, supposition, or assumption believed but not known for certain.

Transcripts of the three protocols were studied to find the questions and conjectures in each protocol. Those questions and conjectures that related to the design artifact or its requirements (as opposed to questions about the protocol process) were used to generate the

**Table 1. Taxonomy of questions and conjectures**

- CATEGORY:
  - Simple conjecture
  - Conjecture with verification
  - Verification question
  - Open question
- TOPIC:
  - Assembly
  - Component
  - Interface
  - Feature
- AGE OF TOPIC:
  - Old
  - New
  - Specification
- NATURE:
  - Construction
  - Location
  - Operation
  - Purpose
- CONFIRMATION:
  - Unconfirmed
  - Confirmed by:
    - Examiner
    - Drawings
    - Specifications
- VALIDITY:
  - True
  - False
  - Unconfirmed
  - No conjecture

taxonomy presented in Table 1 and then classified according to that taxonomy. The questions asked and the conjectures formed by the subjects were studied to evaluate the classes of information that the designers were interested in: information that should be available from an intelligent CAD system.

## TAXONOMY OF QUESTIONS AND CONJECTURES

The analysis of the protocols focused on the questions that the subjects asked and the conjectures that the subjects formed according to the above definitions. Those questions and conjectures that related to the design artifact were classified according to the taxonomy shown in Table 1, above. A definition of each of the terms is given below.

### Category

Question and conjecture passages are classified as being either conjectures or questions according to the above definitions. Conjectures are categorized as being either *Simple conjectures* or *Conjectures with verification*; questions are similarly categorized as *Open questions* or *Verification questions* according to the following:

*Simple conjecture:* A conjecture formed with no apparent, immediate attempt at verficiation.

e.g. 'I think this is for mounting.'
'I think this is steel.'

*Conjecture with verification:* A conjecture immediately followed by a verification attempt.

e.g. 'I think this is for mounting. Is that right?'
'I think this is steel. Is that right?'

The conjecture may or may not actually be verified by the examiner or other outside source. The passage is classified here by its format only, not by the response.

*Verification question:* A question formed such that a simple answer is all that is required by way of response. These are primarily yes or no questions formed when the subject wants to verify a single, conjectured plausible answer.

e.g. 'Is this for mounting?'
'Is this steel?'

Also in this class are disjunctive questions asked when the subject has conjectured two feasible answers.

e.g. 'Is this for mounting or for strength?'
'Is this steel or aluminium?'

Note that questions of this form are classified as *verification questions* whether or not they are explicitly verified.

*Open question:* A question asked requiring a detailed answer. Formed when the subject has no clear idea of what the answer might be.

e.g. 'What is this for?'
'What is this made of?'

The number of questions and conjectures in each of the four categories formed by each of the three subjects appear in Table 2, below.

All three protocol subjects formed approximately two questions for every one conjecture. The ratio of verification question to open questions is fairly consistent for the subjects as well, varying from about one-to-one to two-to-one. There is a striking difference, however, in the ratio of simple conjectures to conjectures with verification among the subjects. S10 formed 7.7 simple conjectures for every conjecture with verification; for S11, this ratio is roughly one-to-one; S12, however, formed more conjectures with verification than without, forming only 0.6 simple conjectures for every one conjecture with verification. In analysing this, it must be acknowledged that S10 worked longer on the protocol than the other two subjects, changing more and forming more conjectures about *new* topics (see below). Since the examiner was present expressly for purposes of helping with the *old* design, these *new* conjectures are more likely to be simple conjectures rather than conjectures with verification or either type of question.

**Table 2. Category of questions and conjectures by subject**

| | *S10* | *S11* | *S12* | *Combined* |
|---|---|---|---|---|
| Simple conj. | 116 (58%) | 32 (33%) | 18 (25%) | 166 (45%) |
| Conj w/verif. | 15 (7%) | 34 (35%) | 30 (42%) | 79 (21%) |
| Verif. question | 37 (18%) | 15 (15%) | 16 (22%) | 68 (18%) |
| Open question | 34 (17%) | 17 (17%) | 8 (11%) | 59 (16%) |
| | 202 (100%) | 98 (100%) | 72 (100%) | 372 (100%) |

Table 3. Topic of questions and conjectures by subject

| | S10 | S11 | S12 | Combined |
|---|---|---|---|---|
| Assembly | 40 (20%) | 18 (18%) | 7 (10%) | 65 (17%) |
| Component | 74 (37%) | 37 (38%) | 12 (16%) | 123 (33%) |
| Interface | 31 (15%) | 18 (18%) | 10 (14%) | 59 (16%) |
| Feature | 57 (28%) | 25 (26%) | 43 (60%) | 125 (34%) |
| | 202 (100%) | 98 (100%) | 72 (100%) | 372 (100%) |

## Topic

The *topic* of each passage is also identified. The *topic* is defined as the design object that the question or conjecture focuses on. If the question or conjecture were in the form of a simple sentence, the topic would be the noun or the subject of the sentence. All questions and conjectures are classified as belonging in one of the following four categories (all examples are from the protocols):

*Assembly:* The topic of the question/conjecture is an assembly, either the complete assembly or a sub-assembly.
e.g. 'What is this flipper dipper?' is a question about the entire *assembly* which is the focus of the re-design effort.

*Component:* The topic of the question/conjecture is a single component of the whole structure.
e.g. 'My clamp appears to be OK.' is a conjecture about the clamp which is a single *component* of the design.

*Interface:* The topic of the question/conjuncture is the relationship or interface between two or more components or assemblies.
e.g. 'How does this pivot arm seat in (the mounting brackets)?' is a question about the *interface* between two components of the design.

*Feature:* The topic of the question/conjecture is some specific feature of some assembly, component, or interface.
e.g. 'I've got 11 1/2 inches, it appears, on the interior of this frame.' is a conjecture about a dimension which is a *feature* of a component.

The number of questions and conjectures in each of the four topics by each of the three subjects appears in Table 3.

The proportions were surprisingly consistent among the three protocol subjects with one exception. S12 tended to focus more questions and conjectures on the *features* of the design than the other subjects, information at the finest level of detail. This may be due to the different character of the problem that S12 worked on.

## Topic age

The topic is further identified by its relative age according to the following classifications:

*Old:* The topic of the question/conjecture is some aspect of the original design as it existed before the current re-design effort.
e.g. 'Does the original flipper dipper work (well)?' is a question about some aspect of the *old*, or un-modified, design.

*New:* The topic of the question/conjecture is some aspect of that design as modified during the current re-design effort.
e.g. 'Would it matter where I mount this micro-switch?' is a question about some aspect of the *new*, or modified design.

*Specification:* The topic of the question/conjecture is some aspect of either the original specifications or changes to the specifications.
e.g. 'These are what kind of plates, aluminium plates?' is a question about the design *specifications*, in this case the original specifications.

As shown in Table 4, below, 13% of the questions and conjectures observed relate to the *specifications*. This indicates that specification information should be available to designers. Fifty one percent (51%) of the questions and conjectures had to do with *old* topics, topics that would be contained in any information resource for an existing design. The remaining 36% of the passages related to the changed design (in other words, *new* topics). A static design information tool would not address new topics, but a design tool that recorded design histories as the design was in progress would.

There are great differences between the subjects in this area, but all subject referred to all *ages* of design information.

## Nature

In addition to identification of the topic, each question

Table 4. Topic age of questions and conjectures by subject

| | S10 | S11 | S12 | Combined |
|---|---|---|---|---|
| New | 100 (50%) | 29 (30%) | 5 (7%) | 134 (36%) |
| Old | 81 (40%) | 51 (52%) | 58 (81%) | 190 (51%) |
| Specification | 21 (10%) | 18 (18%) | 9 (12%) | 48 (13%) |
| | 202 (100%) | 98 (100%) | 72 (100%) | 372 (100%) |

**Table 5. Name of questions and conjectures by subject**

| | *S10* | *S11* | *S12* | *Combined* |
|---|---|---|---|---|
| Construction | 105 (52%) | 46 (47%) | 24 (33%) | 175 (47%) |
| Location | 37 (18%) | 19 (19%) | 26 (36%) | 82 (22%) |
| Operation | 47 (23%) | 22 (23%) | 5 (7%) | 74 (20%) |
| Purpose | 13 (7%) | 11 (11%) | 17 (24%) | 41 (11%) |
| | 202 (100%) | 98 (100%) | 72 (100%) | 372 (100%) |

and conjecture is characterized according to its *nature*. The *nature* is identified by the type of information that the subject either seeks (as in a question) or presumes (as in a conjecture). While the *topic*, discussed above, indicates which class of design object the question or conjecture refers to, *nature* defines what about that design object the subject is interested in. The four natures of questions and conjectures are identified below.

*Construction:* The question/conjecture concerns the physical structure of a design object, the manner in which a design object is made including material, shape, etc.
e.g. How is this built?
'I've got 11 1/2 inches, it appears, on the interior of this frame.' is a conjecture about the *construction* of a component.

*Location:* The question/conjecture concerns the position of a design object with respect to some reference, where a design object is with respect to some other design object or in some reference frame.
e.g. Where is this?
'The plate comes within 1/8 inch from this edge. Right?' is a conjecture (with verification) about the *location* of one design object with respect to another.

*Operation:* The question/conjecture concerns the behaviour of a design object, the manner in which the design object performs its intended function.
e.g. What does this do?
'Does (the pivot arm) flip all the way out, or (are there) two positions? is a question regarding the *operation* of the assembled mechanism.

*Purpose:* The question/conjuncture concerns the reason a design object is included in the design, the function a design object is to perform.
e.g. Why is this here?
'Why the 2 inch tubing?' is a question regarding the *purpose* of a feature of a component in the design.

The number of questions and conjectures belonging to each of the four natures formed by the three subjects appear in Table 5.

Between one-third to over one-half of the interest of each subject was in the *construction* of design objects. *Construction* information (as well as *location* information, which was also highly sought) should be contained in any complete design documentation. *Operation* and *purpose* information, on the other hand, is not included in standard design documentation yet is sought by designers when it is available. This information must be stored in intelligent CAD if it is to be available at all.

## Confirmation

Whether or not the question or conjecture is *confirmed* and the source of the confirmation is also noted. Here *confirm* is used in a general sense, not just for confirming correct conjectures; for questions, the term 'answer' may be more appropriate, for mistaken conjectures, the term 'refute' is more accurate.

Note that questions and conjectures confirmed by the subject's expertise are considered unconfirmed for these purposes. The categories of confirmation are:

*Unconfirmed:* no immediate confirmation or answer
*Examiner:* confirmed by the examiner
*Drawings:* confirmed by drawings supplied to or generated by the subject
*Specifications:* confirmed by specifications or changes of specifications provided to the subject

The number of questions and conjectures confirmed by each of these three sources along with the number of unconfirmed questions and conjectures appear in Table 6, below.

As mentioned in the section discussing *category* of questions and conjectures, S10 formed far more simple conjectures and fewer conjectures with verification than the other two subjects. This behaviour is seen again in analysing the *confirmation* of questions and conjectures. Sixty percent (60%) of S10's questions and conjects were unconfirmed (or unanswered) compared to 36% for S11 and 15% for S12. One prime factor in this may be the

**Table 6. Confirmation of questions and conjectures by subject**

| | *S10* | *S11* | *S12* | *Combined* |
|---|---|---|---|---|
| Drawings | 29 (14%) | 9 (9%) | 2 (3%) | 40 (11%) |
| Examiner | 46 (23%) | 53 (54%) | 58 (82%) | 158 (42%) |
| Specification | 5 (3%) | 1 (1%) | 0 (0%) | 6 (2%) |
| Unconfirmed | 122 (60%) | 35 (36%) | 11 (15%) | 168 (45%) |
| | 202 (100%) | 98 (100%) | 72 (100%) | 372 (100%) |

additional training these two subjects received using the examiner's design information during the warm-up sessions, as discussed earlier. Because the examiner worked more closely with subjects S11 and S12 during these warm-ups, they appeared to be more confident using the examiner's knowledge. The fact that the protocol subjects referred to the examiner's stored design knowledge at all indicates that mechanical designers would use design information stored in any intelligent CAD tool if available.

### Validity of conjecture

Validity is a measure of the accuracy of a conjecture. The validity of all confirmed conjectures, including conjectures implicit in verification questions, was determined. The validity of unconfirmed conjectures and the validity of questions without an implicit conjecture was not established. The validity of most unconfirmed conjectures (such as 'I don't know which option is better, but this one looks easier to solve') is impossible to measure with any certainty, while the validity of an explicitly confirmed conjecture is readily determined. *Open questions* and disjunctive *verification questions* do not contain a single conjecture; in these cases *validity* has no meaning. The four categories of validity therefore are:

*True:* The conjecture formed by the subject is a valid conjecture
*False:* The conjecture formed by the subject is not a valid conjecture, it is incorrect
*Unconfirmed:* The question of conjecture was not immediately confirmed
*No conjecture:* There is no clear single conjecture implicit in the question. The passage is a confirmed open or disjunctive question.

Note that a listing of *unconfirmed* here corresponds directly to a listing of *unconfirmed* in the preceding *confirmation* category. If an open or disjunctive question is not immediately confirmed, it is listed as *unconfirmed* rather than *no conjecture* even though no clear single conjecture is present.

The number of questions and conjectures belonging to each of the four validity classes formed by the three subjects appear in Table 7, below.

S10 confirmed far fewer questions and conjectures than the other subjects, as was discussed in the *confirmation* section above, and formed far fewer *true*, confirmed conjectures. This subject had approximately the same percentage of *false*, confirmed conjectures as the other subjects. This would indicate that S10 only confirmed conjectures when the validity was uncertain.

It is theorized that if a complete design information were available, with the data structured such that retrieval was facilitated, more conjectures would be verified and fewer incorrect conjectures would be incorporated into the finished design.

## COMBINATIONS OF TAXONOMIC CATEGORIES

The taxonomy presented above divides the questions and conjectures formed by the three protocol subjects according to six defined taxonomic classes: category, topic, age of topic, nature, confirmation, and validity. These six classes can be combined into fifteen possible pairs. Four of these combinations showing particularly interesting results are presented below (others are discussed in Kuffner[10]). Discussed are question and conjecture:

Nature versus topic
Category versus validity
Topic versus confirmation
Nature versus confirmation

### Question and conjecture nature versus topic

Comparing the *nature* (construction, location, operation, and purpose) of the question and conjecture passages versus the *topic* (assembly, component, interface, and feature) of these passages yields some interesting patterns. The number and percentage of questions and conjectures for each combination of nature and topic is shown in Figure 1, below.

High percentages of questions and conjectures were formed concerning the *construction* of both features and components. Also of high interest were the location of components and the construction of both assemblies and interfaces. Uncommon were questions and conjectures concerning the *purpose* of assemblies or interfaces.

This distribution should guide the design information structure of intelligent CAD systems. The subjects of this study were interested in the construction of design objects, especially features and components, so this information must be included in and readily obtained from an intelligent CAD system. Less important is information on the purpose of assemblies and interfaces. Though the data from three subjects is far from conclusive, the trend is clear.

**Table 7. Validity of questions and conjectures by subject**

| | *S10* | *S11* | *S12* | *Combined* |
|---|---|---|---|---|
| True | 32 (16%) | 42 (43%) | 41 (57%) | 115 (31%) |
| False | 20 (10%) | 6 (6%) | 13 (18%) | 39 (11%) |
| Unconfirmed | 122 (60%) | 35 (36%) | 11 (15%) | 168 (45%) |
| No conjecture | 28 (14%) | 15 (15%) | 7 (10% | 50 (13%) |
| | 202 (100%) | 98 (100%) | 72 (100%) | 372 (100%) |

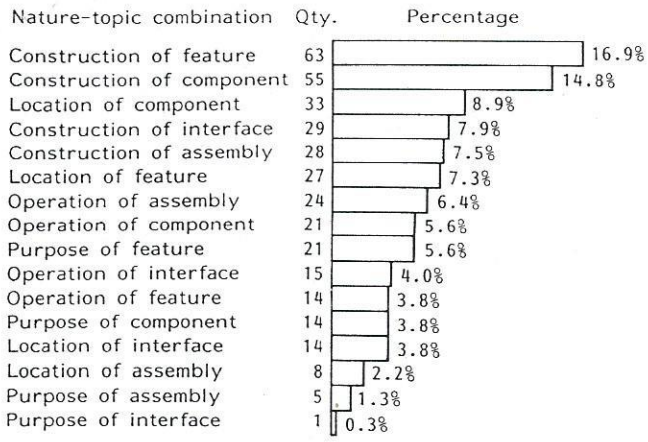


*Figure 1. Question and conjecture nature versus topic*

## Question and conjecture category versus validity

Forty one percent (41%) of the questions and conjectures in the protocols contained conjectures that were externally confirmed (simple conjectures, conjectures with verification, or verification questions with a single implicit conjecture that was confirmed). The validity of these conjectures was determined as either *true* or *false*. Twenty five percent (25%) of these *measurable* conjectures were false. This result is quite flat across the three question categories that can be deemed true or false as is illustrated in Figure 2, below.

The fact that this response is flat runs counter to the hypothesis that simple conjectures are formed when the subject is fairly confident in the acccuracy of the conjecture, conjectures with verification when less sure, and verification questions when still less sure. This result would indicate that the three conjecture types are all about equally likely to be valid. On the other hand, because of their format, simple conjectures are less likely to be confirmed, and the validity of unconfirmed conjectures was not determined. Eighty one percent (81%) of the simple conjectures went unconfirmed compared to only 6% of the conjectures with verification, 19% of the verification questions, and 27% of the open questions. The unconfirmed *questions* (of both the verification and open type) were primarily rhetorical questions, questions that did not require an answer.

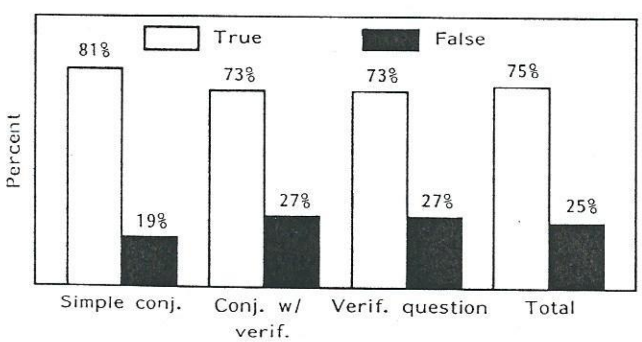


*Figure 2. Validity of conjectures by category*

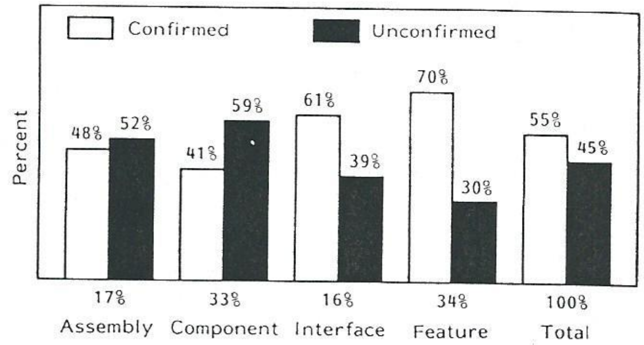


*Figure 3. Confirmation of conjecture by topic*

## Questions and conjecture topic versus confirmation

Next consider the *topics* of the questions asked and the conjectures formed (assembly, component, interface, and feature) versus the *confirmation* of these questions and conjectures (examiner, drawings, specifications, and unconfirmed) as shown in Figure 3, above. The source of confirmation of the questions and conjectures across all topics is fairly flat proportionally, with 77% of those confirmed, confirmed by the examiner, 20% confirmed by drawings, and the remaining 3% confirmed by the problem specifications. The proportion of questions and conjectures confirmed by any source to unconfirmed questions and conjectures, however, is not as well behaved. Feature based questions and conjectures are confirmed 70% of the time, compared to an average 55% confirmation rate. This higher confirmation rate would imply that *feature* information, information at the finest level of detail, is more critical, therefore more likely to be confirmed than other, coarser design information.

## Question and conjecture nature versus confirmation

In studying the nature of questions and conjectures (construction, location, operation and purpose) versus confirmation (examiner, drawings, specifications, and unconfirmed) one significant trend becomes apparent. As shown in Figure 4 below, questions and conjectures pertaining to the *purpose* of a design object tend to be

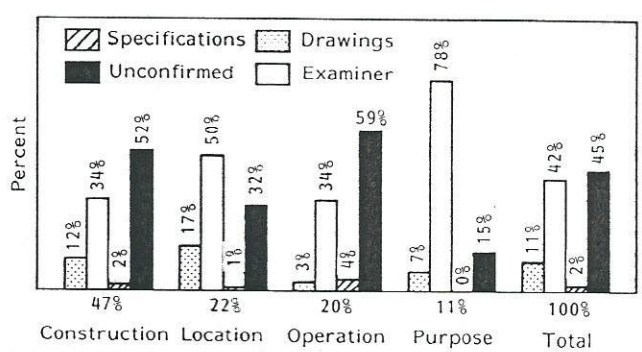


*Figure 4. Source of confirmation by nature*

confirmed, and confirmed by the examiner, in higher proportion than questions and conjectures regarding the other natures.

Eighty five percent (85%) of the *purpose* oriented questions and conjectures were confirmed, 91% of these were confirmed by the examiner. This compares to 55% of all questions and conjectures which were confirmed, 77% of which were confirmed by the examiner. This result was consistent for all subjects. The reliance of the subjects on the examiners knowledge about the design in confirming *purpose* questions indicate two things: (1), the subjects were uncertain of any purpose conjecture they were able to form, and (2), the other forms of design documentation available (i.e. drawings and specifications) are unsatisfactory in answering *purpose* oriented questions and confirming *purpose* oriented conjecture. This being the case, intelligent CAD must provide *purpose* information to supplement the other documentation forms.

## LIMITATIONS OF THE RESEARCH

This study is exploratory not definitive. The limited numbers of subjects, limited number of design tasks, and simplicity of the design tasks give an indication of the design information sought by mechanical design engineers, but this does not constitute a rigorous, thorough study.

The protocols of the three subjects total over five hours. A total of 372 questions and conjectures were identified from these protocols and studied. While the results of the study are not conclusive, they are revealing. The researchers believe that mechanical design engineers working on other design problems will form the same types of questions and conjectures and in roughly the same proportions as the protocol subjects studied. This should be the case, not only for re-design but for other design analysis tasks as well.

The subjects in this study were urged to work naturally. The examiner served as a design information resource without guiding the design process. Any intelligent CAD tool might have a strong influence on the design process. This different process might affect the information requests made by the designers. Any proposed user interface should be tested to determine the influence on the designers' information requests.

## CONCLUSIONS

This study showed that mechanical design engineers are interested in design information other than that which is contained in standard design documentation consisting solely of blueprints and specifications. This additional information should be made available to working design engineers. The need is evident from the following results.

Of the 372 questions and conjectures studied in the three protocols, 115 (31%) were concerning the operation or purpose of a design object. Seventy eight percent (78%) of the purpose questions and conjectures were confirmed by the examiner. Operation and purpose information is not typically contained in standard design documentation. Intelligent CAD should prove to be an ideal medium to provide this information.

Forty two percent (42%) of the questions and conjectures in the protocol experiments were confirmed by the examiner (with training, this percentage increased). Some of this information was available from the documentation provided. The subjects, however, relied on the examiner because of the ease with which the information was available. The examiner was the only available resource, however, for much of this information. Access to this design information had immeasurable impact on the design. Forty five percent (45%) of the questions and conjectures went unconfirmed. Any tool developed to store and replay design information should have an interface which facilitates retrieval. If a tool were available which contained complete design information structured in such a way as to facilitate retrieval, more questions would be answered and more conjectures would be verified.

Ten percent (10%) of the confirmed conjectures formed by the subjects were false; 75% of these were refuted by the examiner. If this source of design information had not been available, these false conjectures would have likely been incorporated into the design.

The proper tools must be developed to structure, capture and re-play design information. Special interest should be paid to include information which is not contained in drawings and specifications. Intelligent CAD tools provide an ideal platform for storing additional design information.

The work explored the possibilities of having supplemental design information available to mechanical engineers making modifications to existing designs. The research suggests the utility of an intelligent CAD tool to provide this information. As this tool is being developed, further research needs to be performed.

Researchers need to develop efficient methods for capturing, storing, and re-playing design information. Research should also investigate the impact of additional design information on the design process. Other uses of supplementary design information should be investigated. While this study focused on engineers making modifications to existing designs, design understanding is a crucial factor in many other activities.

This study has shown that current design documentation is not complete, and it shows specific areas where supplemental design information was requested and used by mechanical design engineers. Further steps are needed to make full use of information discovered in this research.

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