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Augmenting the House of Quality with Engineering Models

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Abstract

To develop successful products the "Voice of the Customer" must be explicitly considered in the design process. The House of Quality is an increasingly popular structured methodology for ensuring customer focus. In this paper, we describe preliminary work on augmenting the House of Quality through the use of engineering models of product performance. Using an example drawn from practice, we discuss practical problems with using the House of Quality and show how information from engineering models can be used to solve some of these problems. We identify some of the potential benefits of this approach and show how engineering models and the information contained in the House of Quality can be unified in a single representation.
Keywords: House of Quality, modeling, design, product development, representation

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1 Introduction

The degree to which a product satisfies customer desires is a critical product success factor [HOPM90, HOMP89]. A consensus is rapidly developing in industrial practice that customer desires can only be obtained from actual contact with the customer and that designers are often wrong when they try to guess what the customer wants [GRW86, RM83, Ran89, SC78, UH80]. To facilitate customer focus, several structured methodologies for organizing and presenting customer information have been developed. One such methodology is the House of Quality (HOQ), which helps product designers to identify explicitly customer requirements, relate them to objective engineering characteristics, identify tradeoffs, and to evaluate the characteristics of a potential product relative to competing products [CH88].

The HOQ is most often used to set targets for the engineering performance of a product. In a typical situation, marketing staff collect data about customers and competing products and, with some input from engineering, decide a set of performance targets which are then communicated to the designers. In this paper we address two weaknesses of this methodology,

1. Targets set on customer information alone are often unrealistic. Hence designers cannot achieve them and this results in time-consuming iterations until a compromise is reached.

2. The roof of the HOQ alone cannot adequately capture the complex coupling between design variables. Hence the trade-offs that must be made in the design are over-simplified or even ignored.

We believe that engineering models, if used in conjunction with the HOQ, can help address these problems.

Designers often have reliable engineering models which they can use to test the limits of product performance [RUKT91]. The inputs to these models, the design variables, are the actual quantities that the designer can control and the outputs are the important performance metrics of the product. Engineering models can therefore be a valuable tool for exploring design tradeoffs and product performance without building extensive prototype hardware.

In this paper we show how by having access to engineering models and the HOQ simultaneously, designers may more rapidly and reliably produce designs that satisfy the customer. Specifically, we examine shortcomings of the HOQ which manifest themselves when it is used in a real design project and show how augmenting it with mathematical models of product performance helps solve some of these problems. We illustrate all our arguments with an example derived from an ongoing project with an industrial sponsor to design a hand-held power tool. To protect our sponsor's proprietary data, we present our ideas using the design of a cordless drill as the example. The actual project is not

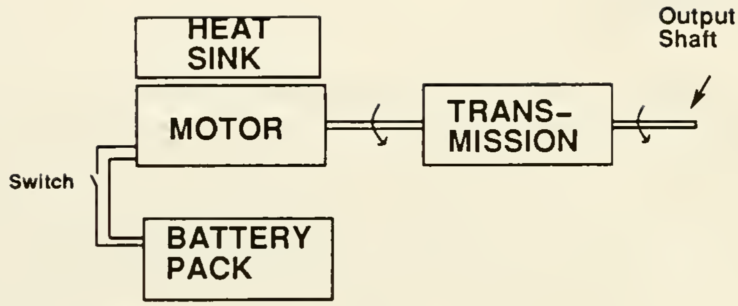

Figure 1: Tool Concept (schematic)

a drill, but shares almost all of the same design issues. The general statement of the disguised design problem is,

> Develop a hand-held cordless drill for the professional market which will take up to 10mm bits and be superior to existing competing products.

We further assume that we are at a point in the development process where we have chosen a basic tool concept. A schematic description of the tool concept is shown in Figure 1. We will show how some fairly difficult decisions must be made even for this simple product and how the HOQ and an engineering model can help designers when making these decisions.

1.1 Roadmap

We first provide some general background on the HOQ and discuss the information stored in it for the cordless drill design example. We then point out some of the shortcomings of the HOQ approach, which we have noticed in the course of attempting to apply it. Subsequently we describe an engineering model of performance for the drill design example and show how references to it can be used to correct some of the problems with using the HOQ. The idea of storing the HOQ and performance models in a single representation to facilitate access and usage is then introduced. We conclude with a summary of the key ideas and an outline of work planned for the future.

2 Using the House of Quality

In this section, we describe the HOQ and explain its use for the cordless drill. Readers familiar with the HOQ technique should skim the generic parts and concentrate on portions related to the design example. Figure 2 contains important information about the example and should be carefully examined and understood before proceeding.

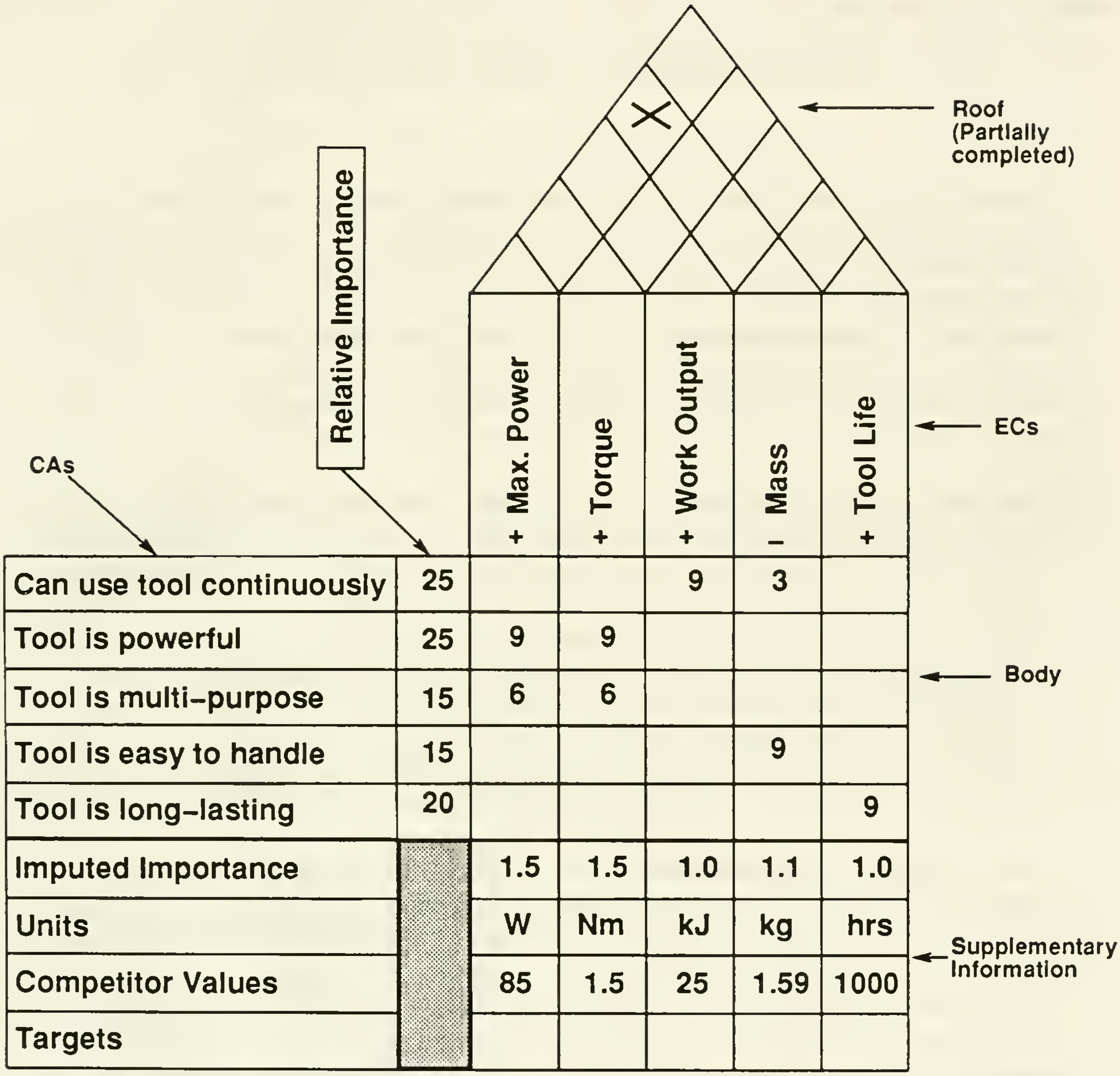

Figure 2: HOQ for design of cordless drill

The House of Quality (HOQ) is a tool for relating the consumers' desires (*customer attributes* in HOQ parlance) to technical performance specifications (*engineering characteristics* in HOQ parlance). Customer attributes collected through surveys and interviews are usually phrased in day-to-day language and are not suitable for direct use in an engineering project. The important objective of the HOQ technique is to help a product development team translate the customer attributes into formal engineering targets and to store the information necessary for this translation in a readable, understandable format. The HOQ related to the design of a cordless drill is displayed in Figure 2. Its elements are:

- *Customer Attributes* (CAs): The CAs are usually actual statements made by customers during interviews and surveys. For example in Figure 2, "Can use tool continuously" and "Tool is powerful" are quotes from actual customer statements. Note also that the CAs shown are actually group headings that arose from arranging the raw customer statements into related groups and then picking one statement which was representative of the whole group. Estimates of the relative importance of the CAs (a total of 100) are typically displayed in a column adjacent to the CA names (see Figure 2).

- *Engineering Characteristics* (ECs): The ECs are the system-level technical product performance characteristics that influence the customer attributes. The designer must be able to assign ECs a numerical value and a unit. Usually ECs cannot be fully identified until a basic product concept has been selected. The values in the "body" of the HOQ (described next) and the relative importances of the CAs can be used to impute importances to each EC. These values are stored as part of the supplementary information in the HOQ. Further, a + or − sign below each EC indicates if the designer wishes to maximize or minimize that value. In our example, *mass* is labelled with − and *max. power* is labelled with + because a tool with low mass and high power is desirable.

- *"Body"*: This is a matrix, having rows labeled with the CAs and the columns labeled with the ECs, whose entries indicate the strength of the relationship between CAs and ECs. In other words each entry indicates how strongly the designer, by changing the EC, can affect the aspect of customer satisfaction represented by the CA. Entries in the body may be symbols or numbers indicating the strength of the relationship. We use numbers on a scale from 0 to 10 in our work (blank spaces in the body in Figure 2 have value 0). Figure 2 shows, for example, that there are two aspects to making the customers feel that they "Can use tool continuously"–*work output* is the major factor (weight 9) and *mass* a comparatively minor one (weight 3).

- *"Roof"*: The roof helps record how ECs interact with other ECs. Engineers often have to "balance tradeoffs when addressing customer benefits" [CH88, GBW92] and hence it is useful to have answers to questions such as "Will lowering the *mass* have any effect on *max. power*?" The answers to such questions are stored in the "roof" of the HOQ, once again in matrix form. An entry corresponding to two ECs indicates that the two are related. In one of the early papers on the subject Clausing and Hauser [CH88], use the symbols $\times$ and $\surd$ to indicate "negative" and "positive" relationships between ECs. For example, Figure 2 shows that *mass* and *max. power* have a negative relationship, indicating that improving the tool power will worsen the tool mass. However, we will shortly illustrate why such simplistic measures of coupling are inadequate in real design situations.

- *Supplementary Information*: The portion of the HOQ below the body is used to store miscellaneous useful information such as target values for each EC, units, and values of that EC for competitors' products (for benchmarking purposes). A particularly important row is the one giving the imputed importances for the ECs. This is computed for each EC as the weighted sum of the correlations with CAs (the relative importance for each CA is the weight). These values are analogous to the relative importances of the CAs. They help guide decisions which hinge on deciding which EC to change so as to realize the maximum possible improvement in customer perception. Often the HOQ includes a region along the right side of the body to show the relative performance of each competitor's product for each CA. This is called a *perceptual map* in marketing jargon. We have not shown this information in Figure 2. Of course, other relevant data may also be stored in the supplementary area and in fact customization to suit individual design problems is encouraged.

3 Two Problems with the HOQ Methodology

The key benefits of the HOQ methodology are that it helps designers answer two fundamental questions. These are (paraphrased from [CH88]).

- How can designers influence customer-perceived qualities and by how much?
- How does an engineering change affect other characteristics?

Let us examine how well the HOQ helps the designer answer these two questions.

The HOQ performs the important function of telling the designers how they currently stand, i.e. how their product stacks up against competing products both in terms of customer perception and engineering numbers. This information, combined with the correlation information from the body, can be used to set targets on the various ECs which will enable the product to outstrip all the competitors. When attempting to achieve these targets the information in the roof is intended to ensure that no EC is improved at the (unreasonable) expense of another.

However, the HOQ does not take into account two important factors.

- Setting targets is of no use unless these targets are realistically achievable. Using customer and competitor information alone to set targets will often result in targets that can never be achieved in practice. ECs cannot be set directly, they can only be indirectly controlled via the design variables for the problem.
- The nature of coupling between ECs can be quite complex and this cannot be stored in the roof of the HOQ because of its extremely limited ability to accurately record tradeoffs. In a typical design situation, two ECs will have several common design variables and the behavior with respect to each of these variables may be different. Hence it is not possible to characterize the true tradeoff with just a single symbol representing a positive or negative relationship.

We believe that these problems are best solved or at least alleviated through the use of engineering models, which are mathematical models of product performance. To reinforce our assertion, we introduce an engineering model for the drill example and show how it can be used to solve the above problems.

4 How Do Engineering Models Help?

Many firms, manufacturing products ranging from bearings to jet engines, have developed engineering models for their products (for an example from the domain of automobile design, see [RUKT91]). These models are used to decide whether designs are feasible, to explore the performance envelope of a design without actually building a physical prototype, and to study the tradeoffs involved in the design. An engineering model is a mathematical model that relates the design variables to the performance metrics used to quantify performance of a product. For example, the engineering model for the cordless drill relates design variables such as *number of cells* and *motor choice* to performance metrics such as *maximum power* and *mass*.

The structure of an engineering model for the cordless drill example is shown in Figure 3. The variables (e.g. *motor choice* and *transmission ratio*) on the extreme right are the design variables for this problem and those on the extreme left (e.g. *max. power* and *mass*) are the performance metrics. Some intermediate variables such as *motor torque* and *overall efficiency* are computed for convenience. The structure of the network in Figure 3 is such that if values are specified for all the design variables, the performance metrics can be computed from them without iteration. As shown in the figure causality flows from right to left in the network.

Using an engineering model to calculate numerical values for the performance metrics is only one use that it can be put to. Another major benefit is the insight it can offer into the topology of the design problem. Network representations, such as the one shown in Figure 3, make it easier for the designer to understand which design variables affect a particular performance metric, how strongly coupled a metric is with another one and so on.

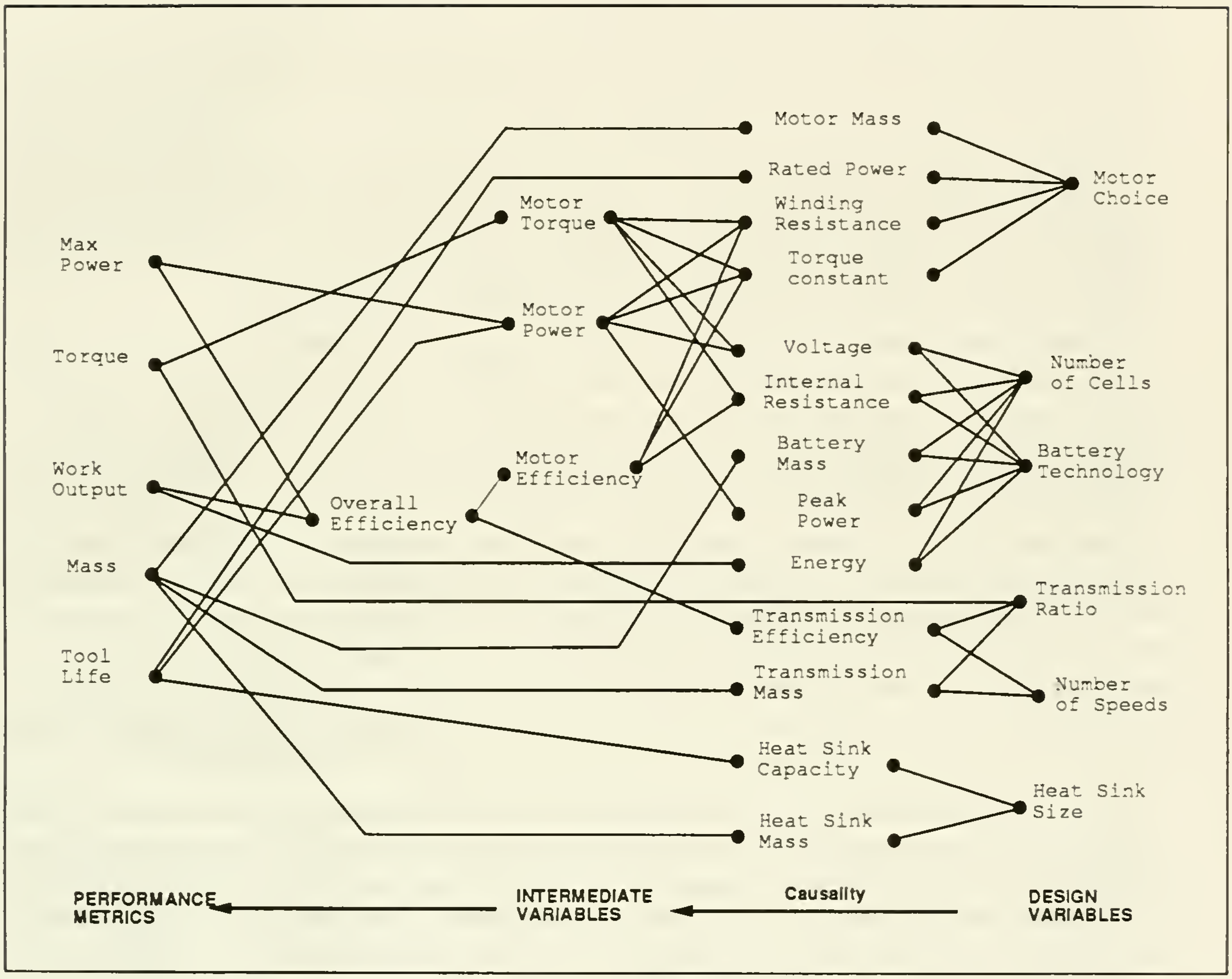

Figure 3: Engineering Model for Cordless Drill

Engineering models are useful in conjunction with the HOQ because they complete the chain from the entities the designers can actually change, the design variables, to what the designer wants to affect, customer perception of the product. We now describe two important ways in which an engineering model linking design variables to the ECs of the HOQ can help us address the weaknesses in the HOQ methodology.

4.1 Setting Reasonable Targets

One of the principal benefits of the HOQ methodology is that it enables subjective customer data to be translated into concrete performance targets. For example, the statement "Want to use tool continuously" does not give a designer much useful information, but a desired *mass* of 2.0 kg and *max. power* of 100 W make the design problem much better defined. Data from the HOQ about customer perception and competing products is often used to determine performance targets for a design. These targets, if achieved, will raise customer perception of the product above that of any competitor.

Unfortunately, this is not always a fool-proof strategy. Very often, the targets set are not achievable and designers may expend considerable resources explaining why the targets are not achievable, deciding new targets, and creating a design that satisfies the new targets. Targets set based on only customer and competitor information seem especially prone to this outcome.

Consider the case of the cordless drill and the ECs *mass* and *work output*. Figure 3 shows that *work output* is related to *energy* and *overall efficiency*. Let's try to change these by changing *energy* which is in turn decided by the battery-related design parameters (assume a fixed value for the *overall efficiency*). The engineering model shows that *energy* goes up if *number of cells* is increased. However, this also increases *battery mass* and therefore *mass*, indicating that *work output* can only be increased at the cost of a heavier tool. Yet customers want low *mass* and high *work output* simultaneously.

Now assume that there are two competitors, C1 and C2 already on the market. C1's market research indicates that customers don't mind a heavy tool if it has a high *work output*, i.e. they don't have to recharge it as often. C2's philosophy is that the customer must not get tired before the battery runs out and hence they offer a lighter tool which has to be recharged more often. The data from both these competitors and for our product is indicated in the following table.

Competitor Name	Tool Mass (kg)	Battery Mass(kg)	Work Output (kJ)
C1	1.59	0.35	25
C2	1.25	0.30	23
Us	1.3	0.33	23

If the best competitor values are selected as the targets for the ECs, the targets would be a *mass* of 1.25 kg and a *work output* of 25 kJ. Let us temporarily assume that the battery is the only component that is to be changed, and that *overall efficiency* is currently 60%. Hence to get a work output of 25 kJ at 60% efficiency, the battery must store 25/0.6 = 41.7 kJ. Current mass of our tool without battery is 0.97 kg and and hence the battery can weigh a maximum of 0.28 kg to meet the 1.25 kg total. Hence the energy density required is 41.7/0.28 = 149 kJ/kg. Now both competitors are using the same battery which supplies around 130 kJ/kg, which is close to the industry standard. Therefore to meet the 149 kJ/kg demand made on the battery is probably unrealistic. The engineering model can include a number of such checks to ensure that designs are physically realizable given the existing technology. Hence, had the model been consulted when this specification was created, it would have been clear that the specification was unreasonable.

A further examination of Figure 3 shows that *work output* is affected by the *overall efficiency* . Hence improving the efficiency is another potential way of satisfying the targets if it is found that batteries are limited to 130 kJ/kg. Another check can now be performed by computing the *overall efficiency* that would be required to meet the specification. 0.28 kg of the 130 kJ/kg batteries will provide 36.4 kJ at 100% efficiency and the tool must provide 25 kJ, hence dictating an *overall efficiency* of 25/36.4 = 68.6%. A further judgment can then be made on whether this is reasonable or not.

We have shown in the preceding example how the engineering model can be used in conjunction with the HOQ to create a more reliable and realistic specification process. In some cases, technological advances can be made in order to break the bounds of the model predictions. However, the engineering model ensures that the development team knows when targets are within the bounds of available technology and when an alternative technology is the only way to achieve a performance target.

4.2 Managing Trade-offs

The HOQ explicitly acknowledges the inherently contradictory nature of typical ECs or performance metrics and hence attempts to provide a facility for balancing contradictory ECs. This facility is the roof of the HOQ, which is used to tell an engineer what kind of relationship two ECs have–positive, negative or none. For example, in [CH88] the signs $\surd$ and $\times$ denote positive and negative relationships respectively. However there is a basic problem with this approach– in a real design it is often impossible to condense the information about how two ECs are coupled into a single symbol such as $\surd$ or $\times$. Carelessly abstracting these tradeoffs can lead to bad designs. We use the drill example to illustrate the complexity of real tradeoffs and suggest an alternative way of storing the coupling between ECs.

Consider for example the two ECs *max. power* and *mass* in Figure 3. These share many common variables including *motor choice*, and *number of cells*. In situations like this, where there are multiple common design variables, there is the potential for the two ECs to be coupled differently with respect to each common design variable.

For example, if we increase *number of cells*, the values of *mass* and *max. power* go up, which are undesirable and desirable changes respectively. This is possibly what Clausing and Hauser [CH88] mean by their $\times$ symbol. However, looking at *motor choice* we see that by changing its value from brushed to brushless it is possible to drive *mass* down and *power* up, which are both desirable changes. This raises the question of how to represent the overall relationship between two ECs in such situations. A precise semantics must be defined for any terms used to describe the relationship between two ECs.

For example, if two ECs are shown as related by a $\surd$ symbol, does this mean that whenever one of the ECs is increased the other one always increases? Such an assumption is unjustified in most cases as it requires that a stringent mathematical monotonicity criterion be fulfilled. Since this is rarely the case, improperly defined symbols can be quite misleading and adversely affect design decision making. We propose that the roof of the HOQ be used only to display a binary indicator of whether coupling exists or not. The most obvious way of checking if two ECs are coupled is to see if they share any design variables in the engineering model. It can be easily seen from Figure 3 that *mass* and *max. power* share some design variables. However this only indicates the presence of coupling and does not define the nature of the coupling. Another level of analysis such as a monotonicity check on the shared variables must be applied to detail the nature of the correlation. This information may be displayed in a table with an entry for each common design variable. Of course, if the coupling varies depending on the values of the design variables the engineering model must be used to evaluate the nature of the coupling for different values of the design variables. The engineering model provides a justifiable mathematical basis for deriving the nature of these relationships.

We believe that by combining the information in the HOQ and the engineering models, designers have a valuable tool for managing tradeoffs, one of the primary tasks required of designers. Once the engineering model is used to understand the nature of the tradeoffs between ECs, the information in the HOQ can be used to complete the connection with customer perception.

5 A Single Representation for both HOQ and PDN Information

We propose representing all information related to both the HOQ and engineering models in a single representation in order to facilitate the kind of reasoning described above.

An appropriate abstract structure for storing this information is the generalized graph, which uses *nodes* as sites for storage of arbitrary kinds of information and *labeled edges* to indicate relationships of different kinds between nodes. These simple entities can be used to represent all the information currently stored in the HOQ and engineering models shown in Figures 2 and 3. Figure 4 shows how this may be done. It shows more details about the graph representation of the HOQ because the graph structure of the engineering model is already evident from Figure 3.

In practice, the graph in Figure 4 is represented in the computer using frames, a construct developed in artificial intelligence (AI) research[Nil80]. The frame representation was chosen for this application because it is flexible and easy to understand, implement and, if necessary, extend. A frame is a data structure that contains a number of slots, each of which can be assigned a value. To represent a graph, a frame is created for each node in the original graph structure and all the information stored at that node, including that about incident edges, is represented as a set of slot-value pairs belonging to that frame. For example, each frame has a slot called *name*, whose value is a unique identifier. A link to another frame can be represented by storing the name of the linked frame as a slot value. No restriction is placed on the value of any slot and hence multiple values, lists, links to multiple frames etc. can be easily handled. All the frames are stored in a database and by searching this database appropriately all the information originally stored in the graph structure can be retrieved. Figure 4 also shows a sample frame for a CA and an EC node.

Two specific points to note about the frame representation are as follows,

- The frames for the CAs, ECs and design variables, despite different appearances, are in fact similar, differing only in the types and values of slots.
- Arbitrary information can be stored in each frame. For example, if a designer wants to store any additional textual information such as the name of the city where the data was collected with each customer attribute, this can be easily accommodated.

We have implemented a system that supports creation and manipulation of frames for storage of design information. This system has features similar to many research and commercial frame-based systems and is implemented using the LISP programming language. The wide variety of computational structures that can be easily created in LISP as well as the availability of an interactive interpreted environment were some of the important features that guided this choice. The implementation is fairly standard (see for example, [CRM80]) and hence details of it are omitted. The designer is provided with the following basic facilities,

- A means of creating and examining frames of arbitrary size and nature in a variety of ways – through input of formatted text files, by using a graphical editor[2] or by typing LISP commands to the interpreter.
- Access functions that allow the user to retrieve and display information from the representation. For example to list all the ECs related to a particular CA (and vice versa).

[2]Not implemented

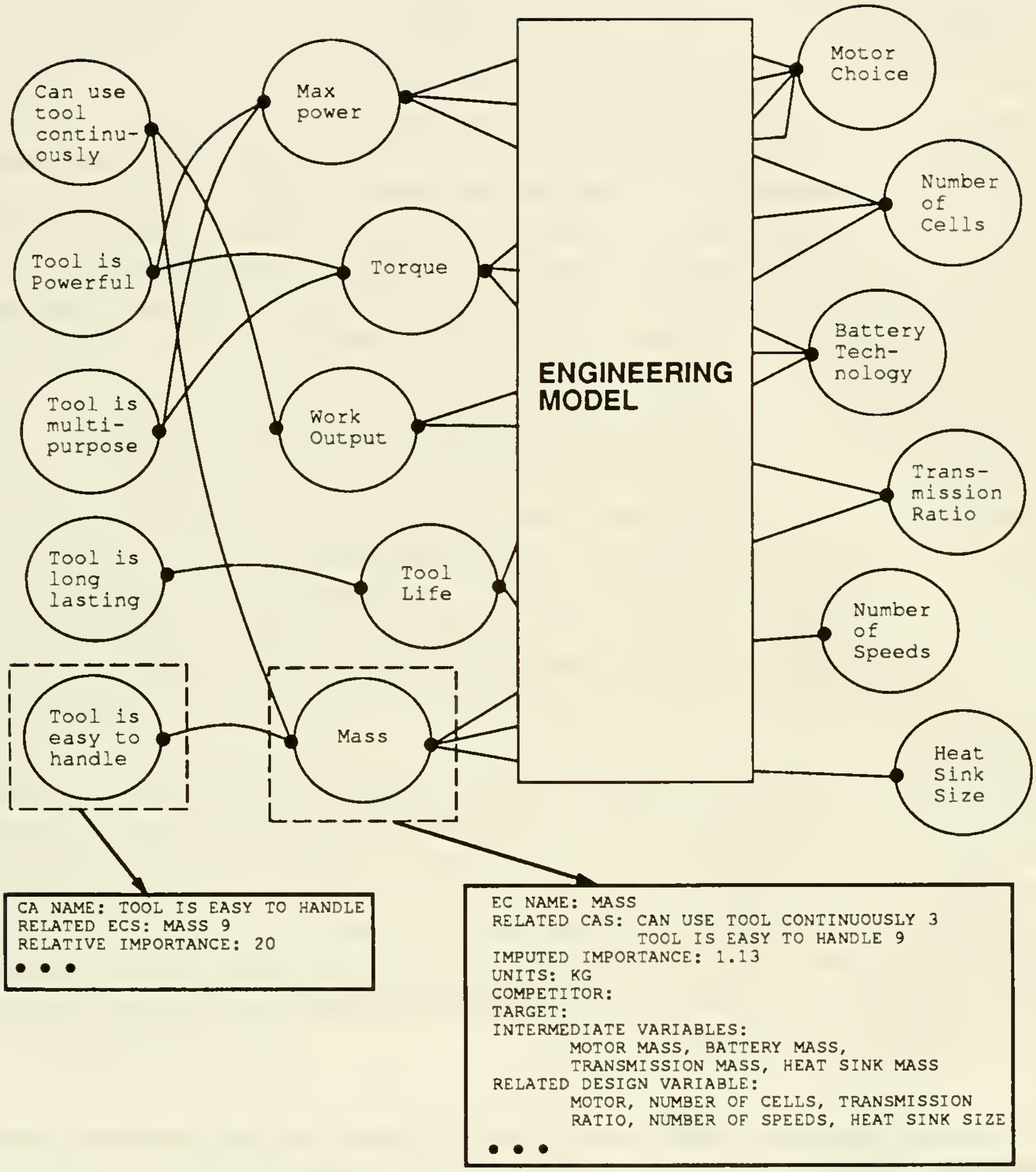

Figure 4: HOQ for design of cordless drill

- Access to the full power of the underlying LISP programming language which can operate directly on the frame representation and be used to perform analyses of arbitrary complexity.

Using a single representation does not in itself add any new theoretical capability that could not be achieved, however awkwardly, by placing printouts of the HOQ and the engineering model side by side on a table. We believe the real benefit of the unified representation is the change we hope it will cause in the way this information is perceived–what was previously mentally labeled "marketing" and "engineering" will henceforth simply be "product design information". We also believe that a unified representation of the information will facilitate bookkeeping, calculations, and other necessary manipulation.

6 Conclusion

6.1 Summary of current work

The aim of this paper is to discuss the following practical difficulties we encountered using the HOQ methodology,

- If the customer and competitor information in the HOQ alone is used to set engineering targets, these targets are often unreachable.
- Using a single symbol in the roof of the HOQ to represent the coupling between ECs is an extreme oversimplification of reality, where ECs are coupled in multiple and complex ways.

We have proposed that these problems can be solved if the HOQ is augmented with the information stored in the engineering models used by the designers. In many product design situations, engineering models are already available and hence can be readily integrated with the HOQ. We have further suggested that in addition to combining this information when reasoning about the design, some benefit can be derived from using a single representation for information contained in the HOQ and the engineering models.

In addition to fixing the two problems mentioned above, we believe there are several peripheral benefits of this methodology.

- The true character of the design problem is more accurately represented since the directly controllable quantities, the design variables, have been linked to the critical output, customer perception.
- The combined information can be used as an effective tool for guiding design improvements because the design variable with the maximum beneficial effect on customer perception can be reliably located.

- Better organizational integration is prompted by the closer link between the marketing and design functions, also resulting in more focussed engineering modeling and customer data collection efforts.

- The number of places in the development process where subjective judgments must be made is reduced.

- The integrated representation facilitates the documentation of design decisions.

Finally, on the subject of structured methodologies for design, we believe that it is important to distinguish the ends and the means. The end is to explicitly take account of potential or existing customers when designing a product so as to eventually achieve a product that better satisfies their needs. The means are structured methodologies. Any one of the several available and proven techniques can, if applied thoughtfully, be used successfully in a design project. It is important to regard structured methodologies in this light and not to treat them as dogma or guaranteed recipes for successful design.

6.2 Future work

This research is still embryonic and important questions remain about the applicability of the ideas presented in this paper. Some of these are:

- Can they be scaled for application to large problems?

- Can they be applied in the context of a real organization?

This question can only be addressed through practical experience and hence we do not attempt to prove or disprove them at this stage. We are currently involved in applying these ideas to a two-year design project, which began in September, 1991 at MIT. The project is aimed at working in conjunction with an industrial sponsor to design, develop and market an innovative power tool. The results of this endeavor are forthcoming and we hope to describe further results based on real experience.

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