Adaptable Modeling of Electrical Systems

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Abstract

Much research in model-based reasoning has concentrated on the use of a single, usually qualitative, level of modeling. This is less than ideal for many engineering applications, where the amount of knowledge available about a product design increases during the design process.

This paper describes a framework that enables a model-based system to use more information about an electrical design as it becomes available. It can provide common results at different stages through the design process, while using more detailed design information to resolve situations that are ambiguous in the qualitative case.

The paper concentrates on the modeling of electrical systems containing electronic and mechanical components, specifically in vehicles, but considers the more general lessons to be learned from this work.

Introduction

Vehicle electrical systems are a good application area for model-based reasoning [Cascio et al., Sachenbacher et al., Price 00]. They are composed for the most part of reusable, self-contained components and typically include both electronic and mechanical components. They also provide an applications "pull" for model-based reasoning, as they can include thousands of components, some with very complex behavior. Analysis of vehicle electrical designs is often done very late in the design process if at all, and the use of qualitative model-based reasoning to automate the analysis is proving increasingly commercially successful [Ward and Price].

The kinds of analysis that can be carried out based on qualitative simulation include:

FMEA. Failure modes and effects analysis considers the effect on an overall product of any (usually single) failure of part of the product.

FTA. Fault tree analysis highlights the combinations of failures that can affect the safety of a design.

Design verification. Given a formal description of the legal states in which a system can be, it is possible to analyze the operation of the design to ensure that the device cannot enter any illegal states.

Sneak circuit analysis. This identifies any unexpected interactions between systems within a product.

Qualitative reasoning is very efficient and provides the best results that can be generated early in the design process, but is incapable of using more detailed information to resolve complex situations, even when such information is available. Ideally, engineers would perform a rough analysis early in the design process to identify gross problems with a design, but would perform a more detailed analysis nearer to product delivery time to pinpoint complex problems that could not be identified precisely until enough information was available.

This paper describes a range of simulation models that can be automatically constructed from schematic information. Simulation results are linked to a common notion of system functionality. This allows the results from different simulators to be compared automatically, and so incremental changes to the analysis results can be identified as the design evolves.

The benefits and drawbacks of the different levels of simulation are analyzed, and more general lessons for model-based reasoning are drawn from the experience.

Architecture of Electrical Qualitative Reasoning

The complexity of the components in vehicle electrical systems has meant that simple reasoning about resistors of the kind portrayed in [Lee, Mauss and Neumann] is insufficient for simulation of such systems. Two levels of reasoning are needed in order to perform qualitative simulation: an electrical qualitative simulation, and reasoning about a component's behavior. The electrical simulator represents the system as a network of resistors and establishes which parts of the system are active using the method described in [Lee]. Above this, there is a level of reasoning which generates such networks of resistors from component models, dependent on the schematic describing the components and how they are linked, and on the state of each component. Changes in the low-level electrical behavior can change the state of the components, and so the reasoning can iterate between the two levels.

The state of each component during a simulation gives too detailed a set of results for use in design analysis, and so the detailed behavior of the circuit needs to be abstracted to obtain a description of the overall behavior of the system

in terms appropriate to the engineers, This is done by identifying the states of significant components which determine the functionality of the overall system [Price 98]. Typically, this will be focused on the effectors of the system (motors, lamps, controllers).

Figure 1 depicts an example of the relationship between the three reasoning levels, showing for a very simple circuit how an electrical network is generated from the schematic, and that the system level functions are abstracted from the state of significant components.
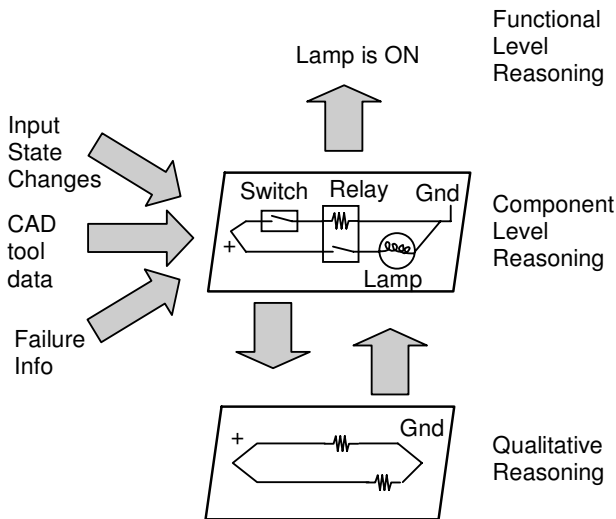

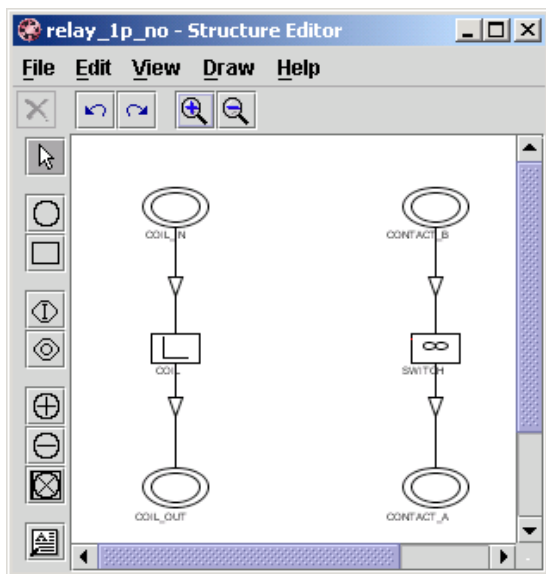**Figure 1: Levels of electrical simulation**

Figure 2: Physical structure of a relay

The major representation task is at the component level. Components are given a network structure and a behavioral description as shown in figures 2 and 3 for a relay. The

physical structure contains dependent resistors that can take values of zero, load or infinity, dependent on the state of the component. The state is changed by outside influence, or by monitoring the current through specified resistors within the component in the present state of the system. For example, the relay's state is changed when current flows through the coil of the relay, and the value of the switch resistor in the relay is then changed from infinity to zero.
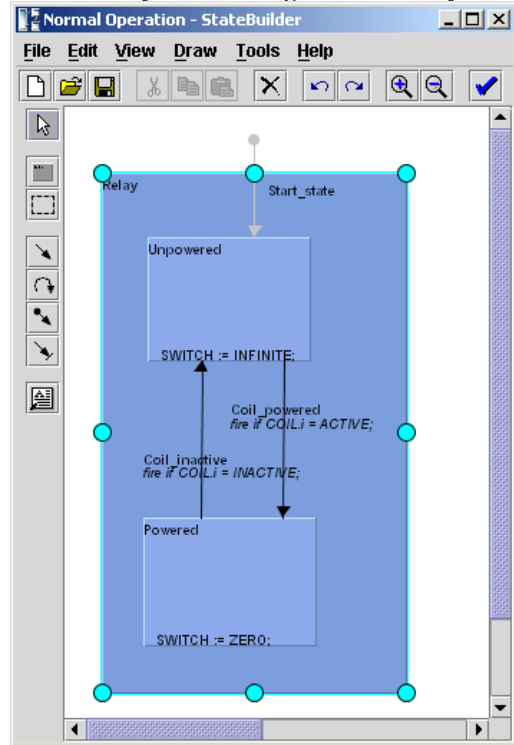

Figure 3: State-based behavior of a relay

At the component level, all behaviour is local to the component with the exception of time. The dynamics of the system are represented by state machine descriptions using an order of magnitude qualitative representation of time [Snooke]. This allows a sequence of qualitative time periods that are applicable to most automotive systems and are assumed to be consistent across many component models:

- instantaneous (electrical propagation);
- μS (ECU operations);
- mS (relay switching);
- S (user interaction);
- hour (battery discharge).

The simulation consists of a sequence of DC electrical analysis steps controlled by the ability of the component level model to change the value of the qualitative resistor

values. Ambiguities in the events sequence are resolved by a simple model of time that considers all component state changes within a qualitative timeslot as concurrent, ie. actions do not take effect until all events in a given timeslot have been completed. We have not encountered any automotive systems where the order of events within a timeslot has any effect on the longer-term behaviour of the system because such situations are normally the result of parallel circuits or otherwise independent events.

The architecture just described has proved very successful for design analysis. It provides a basis for commercial FMEA and sneak circuit analysis tools with the following advantages:

- Design analysis can be performed with very little effort early in the design process, and gross errors detected and rectified. This is the time when it is cheapest to fix problems, and so is a great improvement over performing analysis much later in the process.

- Engineers can explore possible technical solutions without physically building many prototypes - that only becomes necessary once the majority of the problems have been ironed out.

- The software simulates current flow through the circuit using state-based descriptions of complex components, and idealized resistors (with values of zero, load or infinity). This means that early modeling of components is simple and components are very reusable. The library of components needed is much smaller than is the case for numerical simulators.

- It provides the best results possible when all information on specific components used is not available.

However, there are also drawbacks to purely qualitative analysis of circuits:

- Because only idealized resistors are used, it can be impossible to decide what will happen in a circuit. For example, if there is a short circuit, it is impossible to know whether a fuse will blow or wires melt unless the value of the fuse and the length and gauge of the wire are known. The early design analysis can only draw attention to a possible problem to be addressed when detailed design decisions are being made.

- Some types of design analysis cannot be addressed with purely qualitative models. For example, quantitative information is needed to identify whether fusing is correct so that maximum loads do not cause fuses to blow when there is no fault.

- As extra information becomes available about the design, the engineers need to find other ways to verify that problems raised by the early design analysis have been solved. For example, this might mean using the SPICE simulator to get detailed results for a specific failure case.

The need to be able to simulate with more detailed information when it is available has motivated the use of more detailed information where it is available within the software described above. The next section describes the different levels of information that become available, and how they are used to produce more precise versions of the results originally generated by the early design analysis.

More accurate model-based electrical reasoning

The qualitative analysis outlined above works with very little information about the actual physical components used. Drawbacks of this limitation are that some results are ambiguous, and some problems cannot be detected because the models of the components do not have detailed enough information. These drawbacks are a small price to pay for the ability to detect the majority of potential problems early in the design process with comparatively little effort.

However, the analysis results can be gradually improved and tracked as extra information becomes available during the design process. For electrical systems, there are three further kinds of extra information that might become available:

- Knowledge of resistor levels in the circuit
- Knowledge of resistor values in the circuit
- Detailed numerical models for components in the circuit

Knowledge of resistor levels

The qualitative simulation described in the previous section uses three levels of resistance - zero, load and infinite. These are not enough to distinguish between levels of current. For example, a trickle current through a device, say a motor, might be used to provide a signal, where it is not enough to activate the device. The qualitative simulation cannot distinguish between the two levels, and so either compromises must be made in the modeling or resolution of whether current levels are high enough for activation must be left to later in the design process.

Some ambiguous situations can be resolved by adding further levels of resistance. We have implemented a previously described scheme [Lee et al.] which allows an arbitrary number of levels. In practice, in present vehicles, a five level qualitative scheme provides useful extra information in simulation. The qualitative resistance levels are then: zero, low, medium, high and infinite.

The presence of these distinctions allows the visualization to color the circuit with the different levels of activity in the circuit. In a vehicle with a 12 volt battery, the visualization shows three levels of activity as green, yellow and orange. These three levels correspond to information level flow (for activating ECUs), activation level flow (for activating relays), and power level flow (for

activating motors). Allowing multiple values for only the resistance variables avoids the well-known problems associated with many variables containing multiple landmarks [Struss] and provides a similar number of levels of current as the output of the analysis. The levels must have an order of magnitude relation (demonstrated previously by our application semantics). In practice the resistance of an arbitrary number of resistors connected in series cannot be greater than the qualitative resistance of the largest.

In the example given earlier in this section, where a trickle current through a motor provides a signal but does not activate the motor, the abstraction to system level functionality can be refined to recognize that only a large current will power the motor, and the trickle current will not then be mistakenly expected to power the motor.

This scheme can be implemented simply by replacing the lowest of the three reasoning levels described in the previous section. The qualitative reasoner is replaced by the multi-level qualitative reasoner, and information about resistor levels is added to each component type. Extra information needs to be added to the component model, replacing the load values of resistors with high, medium and low loads. This is fairly obvious, depending on the function of the resistor. The simulation then works as before.

Knowledge of resistor values

Later in the design process, once design decisions have been made about specific components to be used, and physical decisions have been made about where to route wires, then precise values of resistors can be provided to the simulation, and the length and gauge of connectors will be known. Resistance values for wires can be automatically calculated from length and gauge details, and quantitative values for resistors in other component models can be easily found by testing the components. Once that information is available, most of the short circuit cases that were identified in early design analysis can be resolved. Without numerical resistor values, it was impossible to tell whether a fuse would blow or a wire melt (if the fusing was wrong). Once resistor values are known, these ambiguous cases can be resolved.

This scheme is also simple to implement within the framework outlined earlier. The lowest of the three reasoning levels described in the previous section is again replaced, and quantitative results are mapped onto qualitative values in the component model. The qualitative reasoner is replaced by a numeric simulator, SPICE, and the network simulation is done in SPICE. The resultant values are mapped onto the qualitative values in the state-based component models at the component level, and the state of components altered in response in the same way as for the qualitative models. Using this approach, only two additional pieces of information are required from the engineer. Firstly the numerical resistance values for components where it cannot be obtained from the schematic component attributes discussed above, and

secondly the thresholds used to map quantitative results (current flow) into the qualitative ones understood by the component level behaviour models. The ability to define the range of numerical values for each qualitative range at a component level is useful since a "negligible" current level (qualitative zero) may be different for different components. For example, up to 10mA for a certain type of relay but 500mA for a large motor. A range is necessary using most numerical simulators because the qualitatively useful values "zero" and "infinite" cause problems for the solvers.

Detailed component models

For specific unresolved problems, or safety-critical systems, the engineers may choose to perform detailed numerical simulation using a commercially available tool such as SABER or PSPICE. We have interfaced the existing design analysis tools to SABER. This works by abstracting the detailed numerical results given by SABER and producing the same English-level results that were provided by the qualitative simulator. As well as producing the type of design analysis results only previously available from the qualitative simulation, this work also provides a much more friendly interface to SABER for performing visualization work.

In this case, both the lower and middle of the three reasoning levels have been replaced by the use of a numerical simulator with detailed numerical models. This has been successfully accomplished, but modeling of components proved to be a significant amount of work, and this would not be an appropriate way of performing analysis for all systems. However, where detailed simulation is needed to take into account factors such as motor inrush currents or lamp filament temperatures, then such detailed modeling may be appropriate.

Results and Lessons Learned

Power windows - a case study

The different types of modeling were implemented for a range of automotive case studies intended to exercise a range of design analysis tasks and a variety of modeling needs. The electrically-operated window system shown in figure 4 is a simple but fairly typical case study.

It allows the driver to operate the driver's or passenger's window, and the passenger to operate their own window, any operation is dependent on the ignition being powered, and there are a number of fuses on the power line.

The case studies were subjected to a number of tests that are typical of the analysis demanded by the automotive industry, and it was determined whether the test was passed with simulation based on each of the possible modeling choices. As well as the standard analyses mentioned earlier of FMEA, sneak circuit analysis and design verification, there are a variety of design issues that would be of interest when examining the design of this circuit:

Resolving current on any bridges. Circuits can be created with multiple paths between two nodes, and connections between those paths. A connection like this between two load paths is a bridge. To be able to analyze the behavior of the whole circuit correctly, components on bridges must be simulated correctly. A 3-levelled qualitative simulator cannot resolve bridges.

No power current flow through ignition switch. Current through this part of the circuit should only be at the activation level (for powering relays), not at the power level (for powering motors etc.).

Voltage drop across motor under constant load. The motor requires 7 amps to operate effectively. The motor has a running resistance of 1.5 Ohms, so 10.5 volts across the motor are required to achieve the 7 amps.

Correct fuse blow under short circuit condition. If a short circuit should occur (for example the coil in the motor shorts) the fuse should blow to stop any damage occurring.

Motor voltage balanced under normal operation. When both motors are running, there should be less than a 0.5 volts difference between the motors.

No fuse blow under motor inrush. The resistance of the coil in a motor is very low. It is only when the motor starts rotating, and the back EMF increases, that the impedance of the motor becomes higher. The fuse should not blow while the motor accelerates and achieves its full resistance.

No fuse blow under stall current for 5 seconds. When a motor is stalled, its resistance is decreased. The fuse protecting the system must not blow under stall conditions for at least 5 seconds.
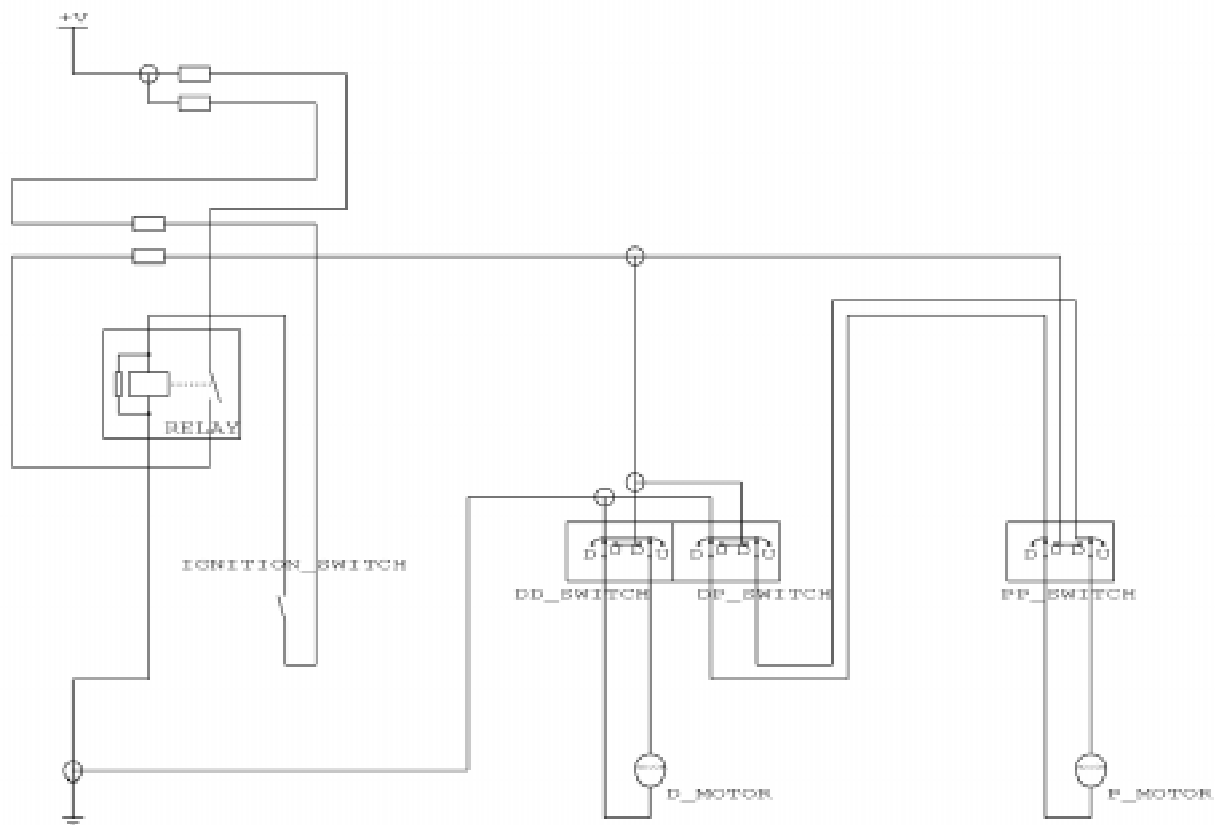

Figure 4: Power windows circuit

The capability of each type of modeling for addressing these design issues for the power windows system is shown in table 1.

It can be seen from this table that the three-level qualitative simulator can perform the basic design analysis tasks for which it was originally conceived, but is incapable of any of the more detailed tasks conceived to show the

limitations of electrical qualitative design analysis. As the information available increases, more detailed modeling can answer an increasing number of the design questions. For the multi-leveled qualitative reasoning and the simple numerical reasoning based on PSPICE, this can be achieved with very little effort by replacing the three-leveled qualitative reasoner with one of the other reasoner and filling in the values - the component-level modeling can be reused from the qualitative version. Where complex numerical simulation using SABER is needed, considerable effort is required in order to provide detailed and effective numerical models for components. Although, as table 1 shows, all the design questions can be answered with this kind of modeling, it would be preferable to avoid the effort unless it is really necessary.

The natural inclination of many engineers is to resort directly to SABER modeling once the qualitative simulator fails to give correct answers. SABER models contain complex coding, and are difficult and time-consuming to build, but where complex, transient behavior is needed, are the only models available which provide the required results. However, in many cases, the scheme using knowledge of resistance values, where the engineer only needs to provide resistance values for the existing behavioral models used by the qualitative simulator provides equally useful answers, for much less modeling effort.

Incremental Automated Design Analysis

In the automotive industry, design analysis has typically been performed towards the end of the product design process. Where changes were made to the design after the analysis had been carried out, it was not possible to completely repeat the analysis, and so engineers would estimate the effects of the change, and limit the analysis to the perceived influence of the change.

Test	3-leveled qualitative	Multi-leveled	Simple numerical	Complex numerical
Failure mode effects analysis (FMEA)	√	√	√	√
Sneak circuit analysis (SCA)	√	√	√	√
Design verification	√	√	√	√
Resolve current on bridges	x	√	√	√
No power current flow through ignition switch	x	√	√	√
Voltage drop across motor under constant load	x	x	√	√
Correct fuse blow under short circuit condition	x	x	√	√
Motor voltage balanced under normal operation	x	x	√	√
No fuse blow under motor inrush	x	x	x	√
No fuse blow under stall current for 5 seconds	x	x	x	√

Table 1: Capability of different simulators

Once the design analysis is automated, it is very little effort to repeat the analysis whenever a change is made to the design. However, that is not the end of the problem. The analysis is only useful because engineers look at the results, and take action on problems identified. A typical FMEA analysis might detail the effect of 500 different component failures, and so an engineer would not want to study each of those 500 results every time a small design change is made.

When the automated FMEA is first performed, the engineer considers all results, and takes appropriate actions. When a change is made to the design (e.g. a new component added to the design), then a new FMEA report is generated. The consistency of the automated analysis results means that software can compare the results after the incremental change with the original results, and report only the differences, Results which have changed are presented to the user, along with any new results (for example, failures on components which did not previously exist). Experiments have shown that instead of being presented with five hundred failure reports to consider for a single change to a circuit, the engineer might only have to study 8 or 10 [Price 96]. This type of technology is also useful when generating diagnostics, in order to deal with the problems of variants on a design and of late design changes. [Price 02].

When extra information becomes available, such that a more detailed simulation can now be carried out, as discussed earlier in the paper, then the analysis results are presented at the same level of system functionality. The incremental FMEA facility can then be applied to detect which results have changed because of the more accurate results available from the more detailed simulation.

For example, say an FMEA based on a multiple-level qualitative simulation has already been carried out and checked by an engineer. When enough detail is available to perform a SPICE-based simulation, then a SPICE-based FMEA can be carried out. The two sets of results can be automatically compared and differences between the two sets of results identified. The engineer might then be presented with the results where qualitative reasoning is unable to decide whether a short-circuit blows a fuse.

These ambiguities are resolved by SPICE, and so the numerical results will be different from the qualitative ones.

This incremental facility, and the fact that it works for a range of simulators means that the implications of detailed design decisions can also be tracked - as resistor values are decided or as resistor values change during the design process, the effects of those decisions on the design can be seen.

The incremental facility has only been implemented for FMEA, but there is no reason it would not work for other kinds of design analysis. The long term implication of the incremental facility for engineering applications is that it provides the possibility of running design analysis each night on all systems where a change to the design has been made during the day, and providing a summary to the engineers the next day of all implications of the design decisions made during the previous day. This would minimize the detection time for any decision which caused a new design problem.

Application to other engineering domains

The work detailed in this paper has been very successful in producing a model-based design analysis system that can give increasingly accurate results as more information becomes available, and can provide the minimum information on the implications of design changes to engineers. It accomplishes this without the engineers having to specify many different kinds of models for components. In part, this success is due to the domain: electrical system modeling is fairly well understood, and the differences between three of the types of modeling are focused on knowledge about resistors. However, there are lessons for other domains.

For domains where component-based qualitative reasoning about flow is done, separation of the qualitative reasoning from component-level reasoning can make it easier to perform reasoning, and easier to replace the qualitative reasoning with numerical reasoning. The qualitative reasoning is often fairly straightforward: the challenges come in switching between operating states of the system. Separating the two types of information makes it easier to perform the qualitative reasoning, and easier to replace it with numerical reasoning.

[Price 98] makes claims for the application of functional labels as an important abstraction mechanism for practical use of qualitative reasoning. The value of that functional abstraction is well illustrated by this system. They work well with numerical reasoning as well as qualitative reasoning. By focusing the results on what is important for design or for diagnosis, they enable automated abstraction of significant results as a design alters. By mapping numerical results onto qualitative ranges, this advantage is available when the design stays the same, but more information is available for the analysis.

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