Explaining how Engineering Devices Work with AGE

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Abstract

Explaining how engineering devices work is important to students, engineers, and operators. In general, machine generated explanations have been produced from a particular perspective. This paper introduces a system called AGE capable of generating causal, behavioral, and functional explanations of physical devices in natural language. AGE explanations can involve different user selected state variables at different abstraction levels. AGE uses a library of engineering components as building blocks. Each component is associated with a qualitative model, information about the meaning of state variables and their possible values, information about substances, and information about the different functions each component can perform. AGE uses: (i) a compositional modeling approach to construct large qualitative models, (ii) causal analysis to build a causal dependency graph, (iii) qualitative simulation to obtain the system's behavior, and (iv) decomposition analysis to automatically divide large devices into smaller subsystems. AGE effectiveness is demonstrated with different devices that range from a simple water tank to an industrial chemical plant.

1. Introduction

Communicating knowledge, in verbal or written form, is an important human learning activity. In engineering, explaining how a particular device works is relevant to engineering students, designers and operators of industrial plants. These explanations, however, are normally given from a particular point of view and without considering the user's particular needs. Machine generated explanations of physical devices normally considered a particular perspective (e.g., functional identification [Kitamura *et al.,* 2002]). Explanations related to a particular device can be given from different perspectives depending on different needs. An engineer may be interested in knowing the causal dependencies between different state variables. She may be interested in observing how the state variables evolve over time, or what is the main function of a particular device. Her interests may focused on particular state variables and/or particular subsystems. All al these explanations are important and provide complementary information to a user. This paper describes a system called AGE (Automatic Generation of Explanations), which can produce explanations of engineering devices in natural language considering different perspectives. In particular, AGE produces causal, behavioral and functional explanations, considering user selected state variables and subsystems.

Webster´s Dictionary offers "giving meaning or interpretation to, or to make understandable" as a definition of explanation, and the goal is to make some piece of knowledge clear to the user. The explanation is complete when the user is satisfied with the explanation and understands the concept being explained. Other dictionaries (see e.g., http://yourdictionary.com) mention that an explanation implied the presentation of a prepositional sequence resulted by

The goal of AGE is create understandability throw the natural language generation of descriptions product of several inferences processes like causal order, qualitative simulation, subsystem reduction. In addition the user select variables and/or subsystems of his own interest. Like expert systems, there is no guaranty of user understanding. In this sense there are no complete, because it does not have an interactive mechanism with the user, that guaranty this. But this does not mean there are no explanation, besides people who used AGE consider it is useful for people and they have no objection to the understanding.

Explanations generated by expert systems normally are how and why type while AGE generate causal, behavior and functional explanation type where the user can select variables and subsystem of his own interest.

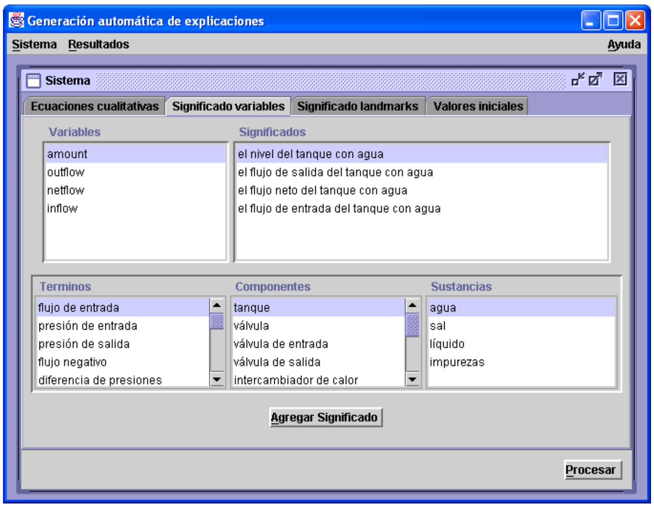
This paper is organized as follows. Section 2 describes the general architecture of AGE and how it produces its different explanations. An evaluation of AGE in terms of applicability and usability is given in section 3. Section 4 reviews related work and section 5 provides conclusions and future research directions.

2 AGE

Physical devices are specified to AGE by joining individual engineering components selected from a library of components through a graphical interface or alternatively by selecting a previously generated device. In AGE, each component of the library, is associated with a qualitative model as specified in QSIM [Kuipers, 1994]. Qualitative models were chosen as they provide an adequate abstraction level from which useful explanations in natural language can be easily produced. In AGE design we consider aspects like:

- resolution, information minimal set, that permit different people design components
- composition, component union in an easy way for systems designers
- quantity representation, for their expression spaces of quantities was consider the most relevant, and
- relation representation, relations between variables, algebraic and differential equations (to represent time change)

The complete specification of a physical component in AGE, requires, besides a qualitative model, the semantic meaning of each state variable and all of its landmark values, as well as its input/output variables in order to connect it with another component. For instance, Figure 1 shows semantic information (in Spanish) associated with a tank filled with water. Each component is also associated with a meaningful name to the user and the name of the substance that it is carrying. In case of chemical reactions within the component, it is the user's responsibility to specify the products.



Variables	Significados
amount	el nivel del tanque con agua
outflow	el flujo de salida del tanque con agua
netflow	el flujo neto del tanque con agua
inflow	el flujo de entrada del tanque con agua

Terminos	Componentes	Sustancias
flujo de entrada	tanque	agua
presión de entrada	válvula	sal
presión de salida	válvula de entrada	líquido
flujo negativo	válvula de salida	impurezas
diferencia de presiones	intercambiador de calor	

Figure 1. Semantic information associated with each state variable. Each variable (e.g., amount highlighted in the upper half) has information about its meaning (*the amount of water in the tank*), they have also information about the substance and related component (e.g., *input flow* highlighted in the lower half, is associated with the *tank* and *water*)

Each time a user joins individual components AGE follows a compositional modeling process (e.g., see [Falkenhainer and Forbus, 1991]) to construct a global qualitative model that takes into account conservation of mass and energy (e.g., the pressure is assumed to be constant between components and all the input and output flow variables of a particular component must sum zero). AGE also identifies the exogenous variables.

AGE's architecture, once a global qualitative model has been constructed, is shown in Figure 2. Given a qualitative model of a particular device, AGE: (i) generates a global flow sheet that is used for functional explanations, (ii) obtains causal dependencies from the qualitative model to produce causal explanations, (iii) simulates the qualitative model to produce behavioral explanations, and (iv) uses this simulation with functional analysis to produce functional explanations. The following sections explain each of these steps in more detail.

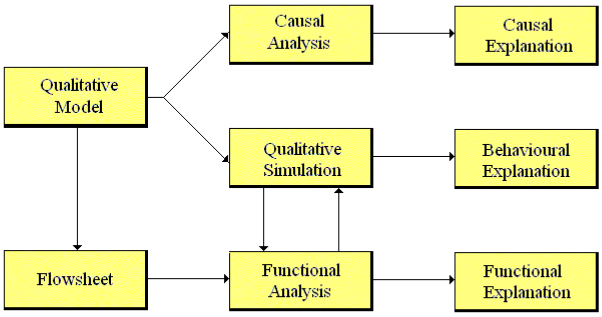


Figure 2 AGE´s architecture

2.1 Causal explanations

An intuitive explanation of a device can be given in terms of causal dependencies of state variables. Given a set of exogenous variables, causal knowledge can be derived from a set of equations using Iwasaky and Simon's algorithm [Iwasaky and Simon, 1993]. The general idea is to build the minimal self-contained system (minimum set of independent *N* equations with *N* variables) and link to the next self-contained system until all the equations are considered (see [Iwasaki and Simon, 1993] for more details).

In a causal graph there is a node for each state variable and a directed link between variable *X* and *Y* ($X \rightarrow Y$) if the values of *Y* depends on the values of *X*.

AGE uses a modified version of this algorithm for qualitative models, which in AGE can be over determined (i.e., with redundant equations), so the causal order is not unique and insert links to represent this information. The criterion was consider first that can not exist link to a exogenous variable, because this implicate a contradiction. If this not happen then the links are collocated in accordance of the syntax equation. So this depends on the number of parameters of each restriction.

For instance, a possible qualitative model of a tank and two valves (see Figure 3) is shown in Table 1, its causal graph is shown in Figure 4, and its causal explanation, considering only flows, is given in Figure 5. AGE produces syntactically correct textual explanations (in Spanish) considering punctuation, gender and number agreement, and reductions to avoid unnecessary repetitions. For example, if a variable depends on another variable of the same component and substance, the component and substance are left implicit and are not mentioned again. The user can also select particular variables to consider in the explanations.

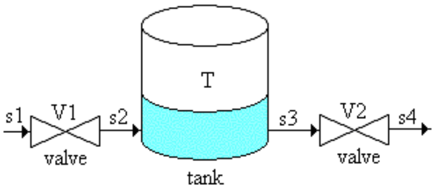


Figure 3 Two valves and a tank

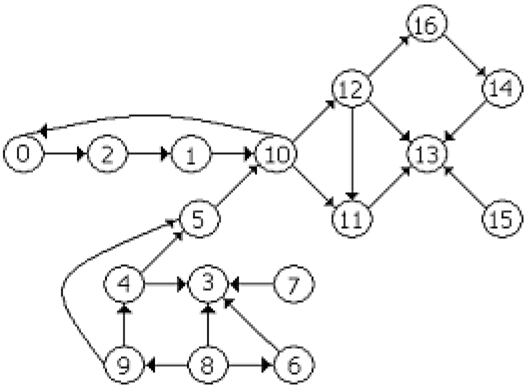
Tank system
minus (V1-MinusQ T-Inflow)
minus (T-Outflow V2-Q)
add (V1-dp T-Pin V1-Pin)
constant (V1-K | k)
M- (V1-Q V1-MinusQ | 0 0 q –q)
mult (V1-Q V1-K V1-dp | 0 k 0)
M+ (V1-Q V1-Pin | 0 0 q p)
M- (V1-MinusQ T-Pin | 0 0 -q p)
M- (T-Amount T-Outflow | 0 0 full –q)
M- (T-Outflow T-Pout | 0 0 -q p)
add (T-Netflow T-Outflow T-Inflow)
deriv (T-Amount T-Netflow)
M+ (T-Inflow T-Pin | 0 0 q p)
add (V2-dp V2-Pout T-Pout)
constant (V2-K | k)
M- (V2-Q V2-MinusQ | 0 0 q –q)
mult (V2-Q V2-K V2-dp | 0 k 0)
M+ (V2-Q T-Pout | 0 0 q p)
M- (V2-MinusQ V2-Pout | 0 0 -q p)

Table 1 Qualitative model after compositional modeling of a tank and two valves. Where V1 = valve1, T = tank, V2 = valve2, Q = flow, K = constant, D = delta (diff.), and P = pressure

To produce causal explanations AGE traverses the causal graph using breadth-first search, considering exogenous variables first and taking care of possible cycles. Explanations are produced in reverse order, where the last node (which depends on the rest of the variables) is used first in the causal explanations. The explanation continues until reaching exogenous variables. To produce causal explanations in natural language, the semantic meaning of each state variable, component and substance is consulted and used to fill-in text templates.

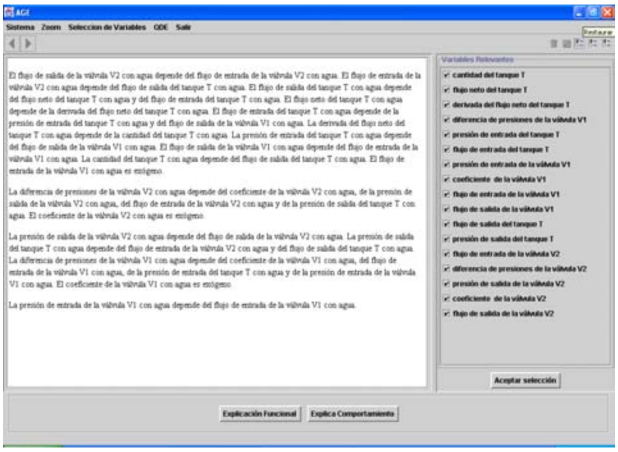
2.2 Behavioral explanations

In order to produce behavioral explanations, for all possible starting states, AGE produces a behavioral graph (a graph where each node represent a particular qualitative state and links represent time sequences) using a modification of QSIM [Kuipers, 1994]. AGE traverses the behavioral graphs to produce behavioral explanations using information about each state variable, component and substance (e.g., see Figure 1), and the semantic meaning of all the landmarks associated to each state variable. AGE uses text templates and syntactic considerations to produce meaningful and syntactically correct explanations.



0	T_Amount	10	T_Outflow
1	T_Netflow	11	T_Pout
2	@T_Netflow	12	V2_Q
3	V1_DP	13	V2_DP
4	T_Pin	14	V2_Pout
5	T_Inflow	15	V2_K
6	V1_Pin	16	V2_MinusQ
7	V1_K		
8	V1_Q		
9	V1_MinusQ		

Figure 4 Causal graph of the qualitative model of a tank and two valves



El flujo de salida de la válvula V2 con agua depende del flujo de entrada de la válvula V2 con agua. El flujo de entrada de la válvula V2 con agua depende del flujo de salida del tanque T con agua. El flujo de salida del tanque T con agua depende del flujo neto del tanque T con agua y del flujo de entrada del tanque T con agua. El flujo neto del tanque T con agua depende de la derivada del flujo neto del tanque T con agua. El flujo de entrada del tanque T con agua depende de la presión de entrada del tanque T con agua y del flujo de salida de la válvula V1 con agua. La derivada del flujo neto del tanque T con agua depende de la cantidad del tanque T con agua. La presión de entrada del tanque T con agua depende del flujo de salida de la válvula V1 con agua. El flujo de salida de la válvula V1 con agua depende del flujo de entrada de la válvula V1 con agua. La cantidad del tanque T con agua depende del flujo de salida del tanque T con agua. El flujo de entrada de la válvula V1 con agua es exógeno.

La diferencia de presiones de la válvula V2 con agua depende del coeficiente de la válvula V2 con agua, de la presión de salida de la válvula V2 con agua, del flujo de entrada de la válvula V2 con agua y de la presión de salida del tanque T con agua. El coeficiente de la válvula V2 con agua es exógeno.

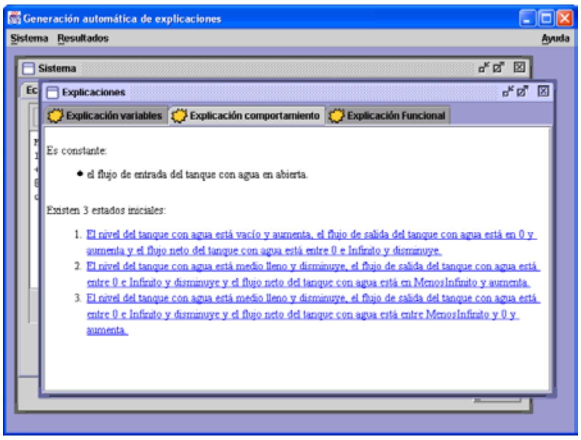
La presión de salida de la válvula V2 con agua depende del flujo de salida de la válvula V2 con agua. La presión de salida del tanque T con agua depende del flujo de entrada de la válvula V2 con agua y del flujo de salida del tanque T con agua. La diferencia de presiones de la válvula V1 con agua depende del coeficiente de la válvula V1 con agua, del flujo de entrada de la válvula V1 con agua, de la presión de entrada del tanque T con agua y de la presión de entrada de la válvula V1 con agua. El coeficiente de la válvula V1 con agua es exógeno.

La presión de entrada de la válvula V1 con agua depende del flujo de entrada de la válvula V1 con agua.

- ☑ cantidad del tanque T
- ☑ flujo neto del tanque T
- ☑ derivada del flujo neto del tanque T
- ☑ diferencia de presiones de la válvula V1
- ☑ presión de entrada del tanque T
- ☑ flujo de entrada del tanque T
- ☑ presión de entrada de la válvula V1
- ☑ coeficiente de la válvula V1
- ☑ flujo de entrada de la válvula V1
- ☑ flujo de salida de la válvula V1
- ☑ flujo de salida del tanque T
- ☑ presión de salida del tanque T
- ☑ flujo de entrada de la válvula V2
- ☑ diferencia de presiones de la válvula V2
- ☑ presión de salida de la válvula V2
- ☑ coeficiente de la válvula V2
- ☑ flujo de salida de la válvula V2

Figure 5 Causal explanation for a tank with two valves. The first sentence says roughly *The pressure difference of valve V1 with water depends on the valve coefficient, its input flow and its output flow*

Each time the behavioral graph branches, AGE creates hypertext links for each branch to facilitate the understandability of the possible qualitative behaviors. For instance, Figure 6 shows tree possible qualitative behaviors of a tank, while Figure 7 shows the explanation produced by AGE, if the user selects the middle link.



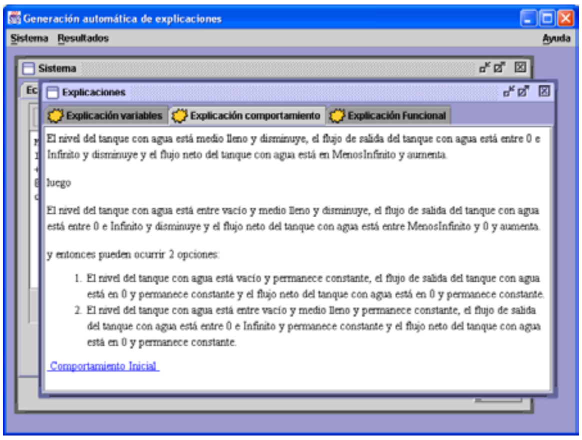
Es constante:

- el flujo de entrada del tanque con agua en abierta.

Existen 3 estados iniciales:

1. El nivel del tanque con agua está vacío y aumenta, el flujo de salida del tanque con agua está en 0 y aumenta y el flujo neto del tanque con agua está entre 0 e Infinito y disminuye.
2. El nivel del tanque con agua está medio lleno y disminuye, el flujo de salida del tanque con agua está entre 0 e Infinito y disminuye y el flujo neto del tanque con agua está en MenosInfinito y aumenta.
3. El nivel del tanque con agua está medio lleno y disminuye, el flujo de salida del tanque con agua está entre 0 e Infinito y disminuye y el flujo neto del tanque con agua está entre MenosInfinito y 0 y aumenta.

Figure 6 Three possible behavioral explanations of a tank. The text says that there are tree possible initial states, the first one says roughly: *The water level of the tank is empty an increasing, the outflow of the tank is 0 and increasing and the net flow of the tank is between 0 and infinite and decreasing.*



El nivel del tanque con agua está medio lleno y disminuye, el flujo de salida del tanque con agua está entre 0 e Infinito y disminuye y el flujo neto del tanque con agua está en MenosInfinito y aumenta.

luego

El nivel del tanque con agua está entre vacío y medio lleno y disminuye, el flujo de salida del tanque con agua está entre 0 e Infinito y disminuye y el flujo neto del tanque con agua está entre MenosInfinito y 0 y aumenta.

y entonces pueden ocurrir 2 opciones:

1. El nivel del tanque con agua está vacío y permanece constante, el flujo de salida del tanque con agua está en 0 y permanece constante y el flujo neto del tanque con agua está en 0 y permanece constante.
2. El nivel del tanque con agua está entre vacío y medio lleno y permanece constante, el flujo de salida del tanque con agua está entre 0 e Infinito y permanece constante y el flujo neto del tanque con agua está en 0 y permanece constante.

Comportamiento Inicial

Figure 7 Explanation of one possible qualitative behavior of the tank. The text roughly says: The water level of the tank is half-full and decreasing, the output flow is between 0 and infinite and decreasing … then the water level of the tank is between empty and half-full and decreasing … and then there are 2 possible options: …

Behavioral explanations are simplified when a state variable follows an increasing (decreasing) behavior through several qualitative states and across several landmark values. For example, consider the consecutive landmarks *LandMark1*, *LandMark2*, …, *LandMarkn* and the following sequence: "*Var1* in *LandMark1* and increasing, *Var1* between *LandMark1* and *LandMark2* and increasing, *Var1* in *LandMark2* and increasing..., *Var1* in *LandMarkn* and constant" is reduced to: "*Var1* increases from *LandMark1* to *LandMarkn*". Finally, user selecting particular variables can also produce new explanations.

QSIM simulation can be very inefficient for large systems. In order to scale-up QSIM to larger devices, AGE divides each system into subsystems at different abstraction levels (as it will be explained in the following section). Our re-implementation of QSIM is used to simulate each individual component from which their behavioral graphs are obtained. Graphs of contiguous components are joined together using connecting nodes (input-output variables) with the same state values and corresponding time stamps. The same process continues (without any further simulation) for contiguous subsystems until a global behavioral graph is constructed. Although more nodes of what are strictly needed may be generated for individual components, they are eliminated during the graph joining process and significant reductions in time are achieved as only simple simulations are performed. To join two or more simulating nodes is necessary that refer to same points in time.

To give an idea of such time reductions, Figure 8 shows a physical device with three components (a mixer, a reactor and a flash separator). Its behavioral explanation was produced in 1/20th. of the time produced with our direct implementation of QSIM without joining behavioral graphs. Furthermore, behavioral graphs of individual components can be stored and used for other systems configuration, substantially reducing the processing time.

Algorithm 1 receive a vector with all the possible abstraction levels of the system and calculate the behavior of each system in accordance with the behavior of the units (subsystems) contained in the system of one major level of abstraction, except the system of minor abstraction level, whose behavior is determined using QSIM directly.

```
NewSimulation (Vector AllDiagrams)
begin
      // Calculate behavior for the system components,
      // minor abstraction level
  diagram ← flow shet of minor abstraction level
  for each unit u of the system
    u.behavior ← QSIM simulation
      //For the rest of the systems
  for each unit d $\in$ AllDiagrams not visited & minor abstraction level
  begin
    sort the susbsystems in a topological order
    for each subsystem sub $\in$ d
      sub.behaviour ← joint behavior graphs of the units in pairs
  end
end
```

Algorithm 1 New Simulation

By simulating individual components and joining behavioral graphs, AGE was able to produce behavioral explanations of the chemical plant shown in Figure 12. For more information about this work please refer [González-Brambila & Morales, 2003].

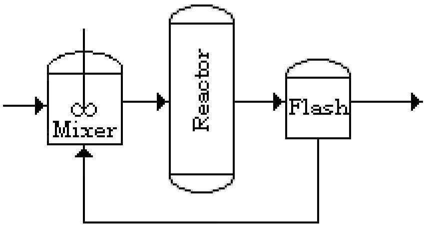


Figure 8 A physical device with three components

2.3 Functional explanations

Each component in AGE is associated with its main function or purpose and a list of secondary functions that may apply under particular circumstances. For instance, the main purpose of a mixer is to mix substances, however, if there is a temperature difference between substances, it can be used as a heat exchanger. To decide which particular function a component is performing, AGE uses information from the behavioral graphs. Although a device may be associated with a particular function, this will not be reported by AGE if it does not comply with its expected behavior (i.e., there is a direct correspondence between behavioral graphs and associated functionality).

AGE produces two types of functional explanations. What we refer to *black box* functional explanations, given in terms of which substances are received and produced by particular components, and more detailed functional explanations, which consider behavioral information. Figure 9 shows an instance of the latter where again syntactic considerations and reductions are employed. It is produced from an acyclic process, which involves a mixer, a pump, a heater, a distillation column, and a condenser (see Figure 10). AGE recognizes that there is a heat exchange in the mixer, due to the behavioral graph. It also simplifies the textual explanation by avoiding unnecessary references. For instance, "*Este flujo alimenta a la bomba B1, se calienta, se destila y se producen s7 y s8*" (This flow is given to pump B1, it is heated, distilled, and s7 and s8 are produced), uses "This flow" in reference to the previously mentioned flow, and the flow is not longer mentioned while it goes through the heater and distiller, until new flows are produced. AGE also recognizes the functionality of the heater and the distiller. Again, AGE use text templates with additional syntactic rules to produce more natural outputs.

Los flujos s1 a temperatura baja, s2 a temperatura alta y s3 a temperatura media se introducen al mezclador M1 se intercambia calor y se produce s4 a temperatura media. Este flujo alimenta a la bomba B1, se calienta, se destila y se producen s7 y s8. Se introduce el flujo s7 al condensador C3 y se producen s9 y s10.

Figure 9 Functional explanation considering behaviors. The first sentence says: The flows s1 at low temperature, s2 at high temperature and s3 at medium temperature are introduced into the mixer M1 there is a heat exchange and s4 is produced at medium temperature

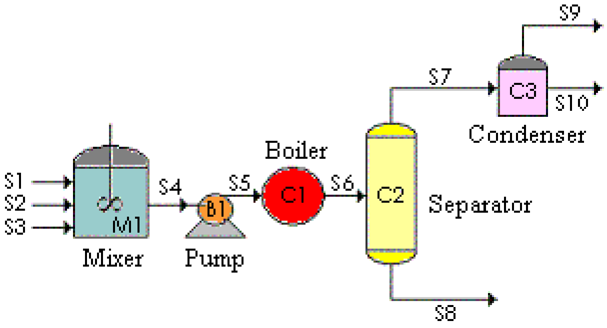


Figure 10 A small acyclic device

In order to understand how a large device works, it is normally required to divide it into subsystems. AGE automatically divides a large system into subsystems using information of the type associated with each individual component using traditional engineering process design priorities (see Table 2). Individual components are grouped considering their priority, where lower priority components are grouped into higher priority components. AGE keeps track of the different components involved in each subsystem and is able to produce functional explanations (following hypertext links) at different abstraction levels. Figure 11 shows the reduction process produced by AGE on a particular plant (the plant shown in Figure 12 has 10 abstraction levels).

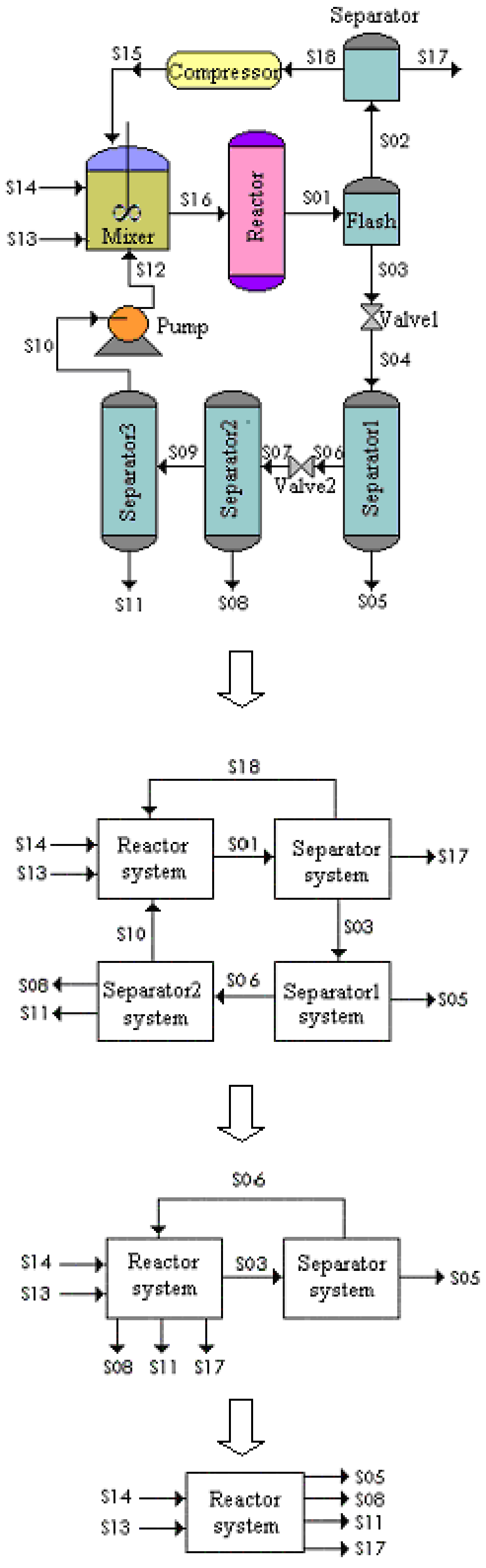


Figure 11 Different abstraction levels of a device. It starts joining together components into the reactor until the whole components are included

Functional explanations can be produced at any abstraction level with links for lower levels. The user can select particular subsystems and or substances involved in the explanations.

Priority	Type	Example
1	Reactor	all types of reactors
2	Separator	filters, centrifuges
3	Energy Transfer	heaters, coolers
4	Material handlers	pumps, compressors, mixers, tubines
5	Storage and control	tanks, valves

Table 2 Types associated to components

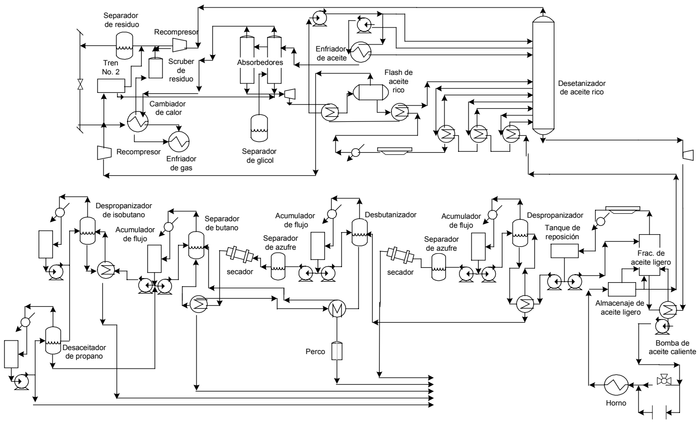


Fig. 12 Empress chemical plant

3 Evaluation of AGE Performance

AGE was evaluated considering two criteria: (i) applicability to a wide range of engineering devices and (ii) utility to engineers.

Using AGE library of components and manually constructed systems, AGE was able to produce causal, behavioral and functional explanations for a wide variety of systems ranging from individual components to industrial chemical plants. Some of these systems involve cyclic flows, different substances, and a wide range of equipment.

To validate the explanations produced by AGE and assess its utility and understandability, a group of student (23) and chemical engineers (9) was also selected. They were presented with 11 systems of different characteristics and dimensions to evaluate AGE performance (all the systems presented in this paper plus additional ones). There were also given a questionnaire to assess the utility of AGE and understandability of the different produced explanations. Although AGE has been only assessed by a small group, it received very positive and encouraging comments.

In the evaluation, with an interval confidence of 95% between 56 and 87% of the people select the modality “very much” and between 7 and 36% “regular” for the utility for the people asked.

The majority of the people consider that AGE has utility to chemical engineers and all people asked consider that is useful to students.

The explanations consider most useful were the behavioral (between 72 and 97% consider "very useful"), then functional explanations (between 64 and 92% consider "very useful") and finally the causal explanations (60 and 90% consider "very useful") all of them with an interval confidence of 95%.

4 Related work

Although, there have been several related proposals in the literature to produce explanations if physical devices, none produces causal, behavioral and functional explanations in natural language.

In [Chong, 1995] a system is described which is used to determine the functionality of a device. It is, however, restricted to function identification, is unable to handle cycles and does not produce explanations in natural language.

A more recent, although similar system, has been developed by Mizoguchi et al. [Kitamura *et al.,* 2002; Sasajima *et al*., 1995]. They use an ontology and a function and behavior representation language to describe the behavior and functionality of a device using also text templates. Their work, however, does not produce explanations in natural language, is restricted to function identification, does not consider sub-systems, and is restricted to thermodynamics.

CyclePad [Forbus *et al.,* 1999] was created to analyze and design thermodynamic cycles and actually is in use. It also uses compositional modeling, performs constraint propagation over numerical models, and responds in natural language to questions related with design of thermodynamic systems and values of particular variables. CyclePad was created as an aid in design, while AGE was created primarily as an aid to engineering students.

AGE is not restricted to a particular type of explanations and the user is able to define what variables or subsystems to consider to meet her particular needs.

5 Conclusions and Future Work

This paper has described a system called AGE capable of generating explanations in natural language from different perspectives and at different abstraction levels. In particular, AGE· uses qualitative models and compositional modeling to create a qualitative model of an engineering device. The qualitative model is used to create a causal graph, which is used to produce causal explanations. The simulation of the model, using a process to join individual behavioral graphs, is used to produce behavioral explanations. Behavioral graphs are also used to identify particular functions of devices. AGE is able to automatically divide a complex system into subsystems, and produce explanations in natural language using user-selected variables at different abstraction levels.

AGE has been tested on several engineering systems and with several users with very promising results. As part of our future work, we would like to produce explanations in other languages, the most obvious candidate being English, and have a friendly user interface to specify new components into the library.

References

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