Tenth Anniversary of the Plastics Color Formulation Tool

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Abstract

Since 1994 GE Plastics has employed a case-based reasoning tool that determines color formulas which match requested colors. This tool, called FormTool, has saved GE millions of dollars in productivity and material (i.e. colorant) costs. The technology developed in FormTool has been used to create an on-line color selection tool for our customers called ColorXpress Select. A customer innovation center has been developed around the FormTool software.

Introduction

With headquarters in Pittsfield, Massachusetts and technical facilities, manufacturing sites and sales locations on five continents, GE Plastics (GEP) produces many of the world's best known and most widely used polymers. In offices and factories ... in hospitals, homes and schools ... on the road and in outer space, products made with GE materials make life simpler, safer and more comfortable for people every day. The plastic GE creates can be made any color that is requested by a customer. Plastic is colored by adding pigments while the plastic is manufactured. In order to determine the correct formulas for our customers, a Case-Based Reasoning (Watson 1997) tool called FormTool was started in 1994.

Prior Art in Color Matching for Plastics

Determining the colorants and loading levels that can be added to plastic so the plastic matches a given color is a difficult problem for multiple reasons. First, the number of combinations of possible colorants is very large. Four to seven colorants are selected from thirty to fifty potential colorants. Second, for each set of possible colorants the amount of each colorant also needs to be determined. Third, there is currently no accurate method to predict the color produced when a set of colorants are added to plastic. Unlike paint, where light primarily reflects off of the surface, in plastics a significant percentage of light penetrates the surface, reacts with the internal structure of the plastic, and can exit the plastic a color that depends on that internal structure. Fourth, a given formula can appear different in different lighting conditions (natural sunlight vs. florescent lighting). Fifth, different base plastics have different starting colors (e.g. clear, white, gray), so the same set of colorant will likely produce a different color in different grades of plastic. GEP makes hundreds of different grades of plastic. Because of these difficulties, selecting the colorants and loading levels for a color formula was previously either accomplished by using human working experience or computationally expensive computer programs. There are commercially available computer programs that can calculate the colorant loading proportions for a color formula that matches a color standard. Since these programs perform an exhaustive search, they require a user to select a subset of the allowable colorants. Usually five to seven are selected out of the thirty to fifty possible colorants. Since the final formula will usually consist of four or five colorants, the users have to make the critical decision of which colorants to select for the search, which often produces a non-optimal solution. Furthermore, it does not take into consideration other important attributes of a color match, such as the cost of the colorants.

We mentioned above that there is no exact algorithm for predicting the color produced by a given set of colorants and loadings. However, the Kubelka-Munk theory (Billmeyer, 1981) can be used to produce an approximation of the color produced by a set of colorants and loadings. This theory describes how the absorption and scattering of colorants in a material are related to the visible color of the material. Each colorant contributes to the absorption and scattering of the material and its contribution is proportional to the amount of it present in the system multiplied by an absorption and scattering coefficient for that colorant. Our system uses Kubelka-Munk theory.

Description of Color Matching Process

GEP provides a color matching service to customers. Customers submit a physical sample of the color they want and GEP either finds a close match from their color library or formulates a new color to meet the customer's needs. GEP currently has over 50,000 previously matched colors on file and performs approximately 4,000 color matches per year. In the past, when GEP performed a custom color match and formula development, there is a significant cost to GEP and the turnaround for the customer average 2 weeks. We looked for ways to reduce this cost and shorten the turnaround time.

Selecting the colorants and loading levels for a color formula was previously accomplished by using a combination of human working experience and computationally expensive computer programs. Figure 1 shows the color matching process that was in place. The process starts with a color matcher inspecting the color

request for the type of plastic, physical color standard supplied by customer, and special properties requested. The matcher would then compare the customer's color standard with previous color chips that were stored in a filing cabinet. The filing cabinet held about 2,000 plastic chips that were about 2" by 3" by 1/8", sorted by color. The matcher would select the most similar color from the filing cabinet. Each chip was labeled and another filing cabinet held a formula card for each chip. The matcher would then inspect the physical chip selected from the filing cabinet to determine if it matched the color and special properties requested by the customer. If it did match, then the formula that was associated with the selected chip would be used for the customer and the match is finished. If the best chip from the filing cabinet was not a satisfactory match, then the matchers used experience along with commercially available computer programs to adapt the colorant loadings. The new loadings would be used to create a small chip containing the adapted loadings. This chip would be compared with the standard. If it was acceptable the adapted formula would be used for the customer and the chip would be placed in the filing cabinet for future reference. If the color was unacceptable then the formula would be adapted repeatedly until an acceptable formula was obtained.
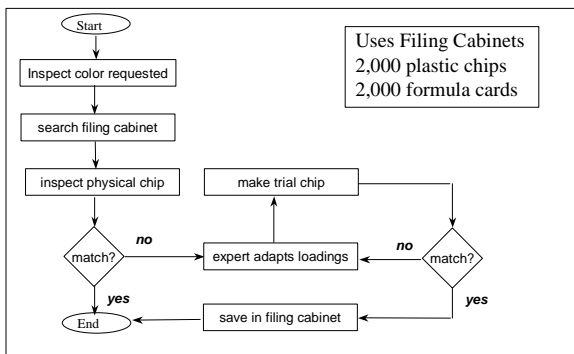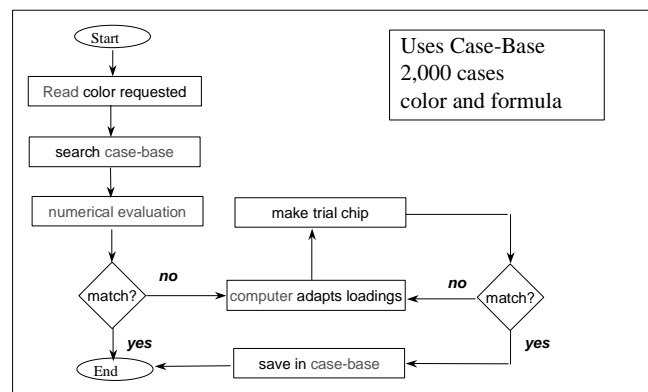

Figure 1: Color Matching Process

FormTool Description

The color matching system consists of a spectrophotometer attached to a personal computer as shown in Figure 2. The spectrophotometer is used to determine a numerical representation of a color, called a reflectance curve. The reflection curve shows the percentage of light reflected by a color at each wavelength of the visible spectra (i.e. 400nm to 700nm). A spectrophotometer reads the reflectance of an object at 31 points equally spaced along the visible spectrum. Comparing two spectra is done by calculating the sum of differences or sum of squared differences between two curves over all 31 points in the visible spectrum. The personal computer contains the case-base and case-based reasoning software, called FormTool. Each case in the

case-base contains a reflectance curve and a list of pigments and loadings used to create that color. FormTool is described below.

Figure 2: FormTool on PC with Spectrophotometer

Figure 3: Automated Color Matching Process

The existing color matching process already followed the CBR methodology so the automated CBR process is very similar to the original color matching process and is shown in Figure 3. The color matcher places the physical color standard in the spectrophotometer and reads the spectrum of the color standard into the color matching system. Next, the color matcher enters key information such as the resin and grade of material in which to generate the match. FormTool then searches its case-base of previous matches for the "best" previous match and adjusts those previous matches to produce a match for the new standard. There are multiple criteria that the color match must satisfy

- The color of the plastic must match the standard under multiple lighting conditions,
- There must be enough pigments to hide the color of the plastic,
- The cost of colorant formula should be as low as possible,

- Only a limited amount of light can be transmitted through the plastic (optical density), and
- The color should not change when the plastic is molded at different temperatures.

The color matcher looks at the physical standard from this previous match and determines if it is acceptable for the application and customer. If the match is not acceptable, FormTool then adapts this previous match so that it more closely matches the requested color and application. The color matcher then makes a physical chip using the adapted formula. If this new match is acceptable then the adapted loadings are saved into the database and the match is finished. If the match is not acceptable then the user can decide to do one of two things:

1) Manually or automatically adjust the color loadings (manual), or
2) Switch to a different previous match as the starting point for this color match (search database)

After one of these is done the cycle continues until a match is found. When the "End" oval is reached, a formula has been obtained that gives the "best" color match and balance of all other important properties.

Case Selection

This section describes a method to evaluate the quality of a specific color formula. A selection process that uses this method to evaluate a formula can be used to find the formula that will reproduce a specified color and meet all desired attributes for the application of the specified color. A nearest neighbor retrieval is used. However, the nearest neighbor must be determined by evaluating the degree of match in all of the attributes described above. This evaluation needs to provide a consistent meaning of an attributes similarity throughout all attributes. The consistency is achieved through the use of fuzzy linguistic terms, such as Excellent, Good, Fair, and Poor, which are associated with measured differences in an attribute. Any number of linguistic terms can be used. A fuzzy preference function (Mendel 1995) is used to calculate the similarity of a single attribute of a case with the corresponding attribute of the subject, see Figure 4. In this figure, a difference of 1 unit in the values of that attribute for the subject and comparable would be considered excellent, a difference of 2 would be good, 3 would be fair, and 4 would be poor. This rating is then transformed into the fuzzy preference function in Figure 4.

The result of using fuzzy preference functions is a vector, called the fuzzy preference vector. The vector contains a fuzzy preference value for each attribute. The values in this vector can be combined, through weighted aggregation, to produce a robust similarity value. The use of fuzzy preference functions allows for smooth changes in the

result when an attribute is changed unlike the large changes that are possible when step functions are used.
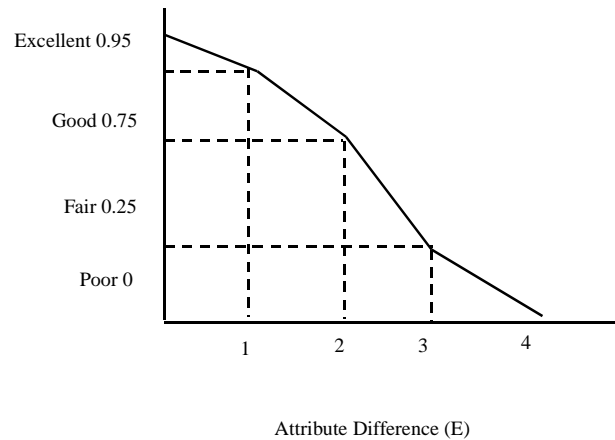
Figure 4: Fuzzy Preference Function

A fuzzy preference function is used to transform a quantifiable value for each attribute into a qualitative description of the attribute that can be compared with the qualitative description of other attributes. A fuzzy preference function allows a comparison of properties that are based on entirely different scales such as cost, measured in cents per pound, and spectral curve match, measured in reflection units. Based on discussions with experts and work to classify previous matches into various sets of linguistic terms we found that there was enough precision in our evaluation of the similarity of the attributes to have four linguistic terms. Table 1 shows the linguistic terms and the numeric similarity score that corresponds to each term.

Table 1: Global Preference Function Scale

Fuzzy Rating	Maximum Score	Minimum Score
Excellent	1	0.95
Good	0.94	0.75
Average	0.74	0.25
Poor	0.24	0

Fuzzy preference functions were created for each of the following attributes of the color match

- Color similarity,
- Total colorant load,
- Cost of colorant formula,
- Optical density of color, and
- Color shift when molded under normal and abusive conditions.

For more details on the case selection see (Cheetham and Graf, 1997).

Case Adaptation

Most formulas that are retrieved need some adaptation. The similarity calculation described above is used to guide the

adaptation. Adaptation is done by repeatedly varying the loadings of the colorants in the formula retrieved and evaluating the new similarity. Kubelka-Munk theory is used as part of the similarity calculation and provides a formula for predicting the color change from modifying the loadings of the colorants. Having a function that can accurately evaluate the effect of an adaptation is the key to performing the correct adaptation.

Hardware and Software Used

The hardware selection was limited to the hardware that was currently available in the color-matching lab. So, FormTool's hardware consists of a spectrophotometer attached to a personal computer running Windows 95. The spectrophotometer is used to determine a numerical representation of a color, called a reflectance curve. The reflection curve shows the percentage of light reflected by a material at each wavelength of the visible spectra (i.e. 400nm to 700nm). A typical color spectrophotometer reads the reflectance of an object at 31 points equally spaced along the visible spectrum. Two spectra are compared by calculating the sum of squared differences, between two curves over all 31 points in the visible spectrum.

The software used to create FormTool required a little more evaluation. Existing case-based reasoning tools were researched. The one that appeared to have the most promise in was ART IM. We created a quick prototype in ART IM, but found that ART IM, in 1994, did not allow the flexibility of case selection needed. Furthermore, GE Plastics systems support would not be able to maintain an ART IM application after it was created. We needed to use tools that could be supported after FormTool was created. A custom development using a Visual Basic front end connected with C++ code for adaptation routines was selected. The case-base was later stored in a Microsoft access database.

Use of AI Technology

FormTool was one of the first AI systems to fully implement the CBR process as described in (Aamdot 1994). When a new color is matched, the case selection algorithms "Retrieve" a set of close matches to that color and related attributes. The "Reuse" of those cases is done by the adaptation algorithms based on color theory. The "Revision" phase is performed by a human who makes a sample batch of the color formula suggested by FormTool. If that formula is proven correct then the solution is confirmed. If the confirmed solution is significantly different that all cases in the current case base, uses different colorants or is greater than a set color difference in Lab color space, then the solution is "Retained" by the case base. It was very convenient that the existing process exactly used the CBR methodology before this project was started.
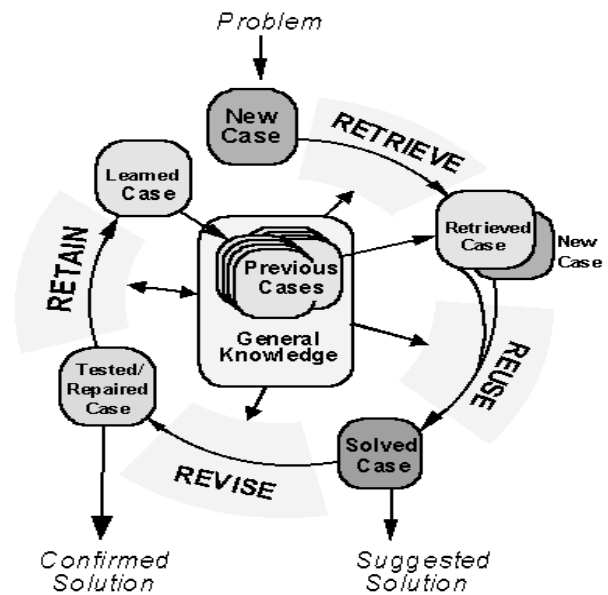

Figure 5: CBR process from Aamodt

Application Use and Payoff

FormTool has been in constant use since its introduction in 1995. During 2004 it was used for an average of 130 custom color matches per week. The following benefits have resulted from using FormTool.

Color Matcher Productivity

The average number of test chips that are created in the Revise phase has decreased from 4.2 to 2.7 per color match. This is an average reduction of 4.5 hours per color match. Since over 5000 color matches are performed per year, this saves 22,500 hours of work per year. The custom color match is a free service for our customers, so the cost of these 22,500 hours would directly reduce our profits. Saving the time directly adds to our bottom line.

Pigment Cost Reduction

Pigments are the most expensive component in plastic. If the amount of pigment that is needed can be reduced then the difference in the cost of the pigment and the cost of the plastic would be saved. This could be a few cents per pound. FormTool's adaptation algorithms were designed to determine the minimum pigment loading that would allow for correct manufacturing of the color desired.

Another way to reduce pigment cost is to use cheaper pigments. Different pigments have different properties and different costs. For example, some red pigments are twice as expensive as other red pigments. The most expensive pigments are usually the easiest to use in a color match. FormTool's case selection algorithms select the best previous match based on cost, and other factors, in addition to the color of the case.

Part of the testing for FormTool that was conducted in 1994 was re-matching 100 colors that had already been matched but still were being manufactured. FormTool found lower cost matches for 64 of the 100 colors. The new formulas were substituted for the old, more costly, formulas. For each of these colors we tracked the number of pounds that were manufactured with the new formula. The cost savings can be calculated by multiplying the difference in cost by the volume for each color then taking the sum for all 64 colors. This was done near the end of 1994. The cost savings were $200,000 in 1994, $1.2 million in 1995, and $1.5 million in 1996. FormTool was used for new matches from 1995 onward. The colorant cost savings for years after 1996 are conservatively estimated at an average of $2.4 million per year.

These cost savings had a critical impact on the Parkersburg plant. Before FormTool, the plant was loosing over a million dollars per year and was slated for closure. This shutdown would have put 100 people out of work in an area where jobs were scarce. Since FormTool and other measures allowed the plant to start making a profit it was not closed and those people did not lose their jobs.

Global Color Consistency

GE has plastics manufacturing sites throughout the world. The consistency of the colors we produce is important to our customers. FormTool has been used to share color formulas. Also, if some pigments are not available in one location, FormTool's case selection can automatically substitute the unavailable pigments with the closest available pigments. This has helped provide globally consistent colors.

A separate tool was created to allow the color matchers to manage the case-base and list of available colors. The manager tool allows the following functionality.

- Import a case base from another location
- Numerically determine the visual properties of a pigment for use in adaptation
- Specify which pigments are available for use
- Specify the price of each pigment.

Other Tool Development

The case adaptation algorithms were used to create a tool for controlling the color produced by a manufacturing line, called LineTool. When colors are manufactured they do not always come out as planned because of many factors. LineTool can determine how to adjust a color that is not exactly on target. It produces a list of pigments that should be added to bring the manufacturing line back on target.

Speed of Color Match

The speed of the color match was very important to many of our customers. For example, if a cell phone maker needed to add a month of time to their development cycle in order to get the various pieces of plastic in the casing to match, they might miss their target date for product

release. FormTool reduced the time needed for a color match. This allowed the color matchers to eliminate the backlog of color matches. Since less experience was needed to perform a color match, resources could easily be added when a spike in demand was received and shifted to other work when there was low demand. Because of the benefits mentioned, the average time from receiving a color match request to creating the formula was reduced by two thirds. At the current writing, 2004, FormTool is used in the countries shown in gray in Figure 6.

Figure 6: Countries with FormTool in Use

Application Development and Deployment

The software engineering paradigm used was the spiral development process. Two developers created the first version of FormTool in less than one year for a total cost of $300K. The first version only worked for one family of plastic, Cycolac, which was manufactured Parkersburg. The initial deployment was only to the West Virginia site. At the system's first demonstration, the manager paying for the project asked the developers to rematch a red color that had just been matched and had not started use in production. FormTool found a match that saved GE $50K on that year's production of that color.

The two developers continued working on FormTool and related projects for the next two years. During these years features were added, a maintenance tool was created, new families of plastics were supported, and FormTool was transitioned to other site in the United States. It was more difficult to transition FormTool to a new site than we expected. Each site had a different color match process. We needed to standardize these processes before FormTool could be transitioned. This standardization involved determining what was the best process, modifying FormTool to meet this process if needed, and convincing people to adopt this process. We recruited a local expert at each site to be the person in charge of FormTool at that

site. The expert's tasks included installing updates, distributing locally added cases, and training others at their site in how to use FormTool.

Globalization of the tool was performed in 1997. The user interface was modified to be in either English or French. The case-base was changed from a local version, which needed user intervention to be updated with downloads of new cases, to a centralized database. In 1998, maintenance of FormTool was transitioned from the two developers to the Information Technology group of GE Plastics.

The creation of FormTool paved the way for other AI tools. In 1996 LineTool was created to help operators of the plastics manufacturing line adjust the color of a batch that is being produced. If samples indicated the color was not correct then a slightly modified version of FormTool was used to determine what pigments to add in order to bring the batch back to the correct color.

In 1997 ColorXpress Select was created as an on-line color selection tool for GE's customers, http://www.gecolorxpress.com/. The case-base from FormTool was used as a color palate that our customers can browse, request samples, and order online. When a customer used this tool it completely eliminated the need for a color match and reduced the time needed for the customer to get their match completed. Any item selected has already been matched and a sample can be sent FedEx to the customer in less than 48 hours. The web page for selecting a formula is shown in Figure 7.
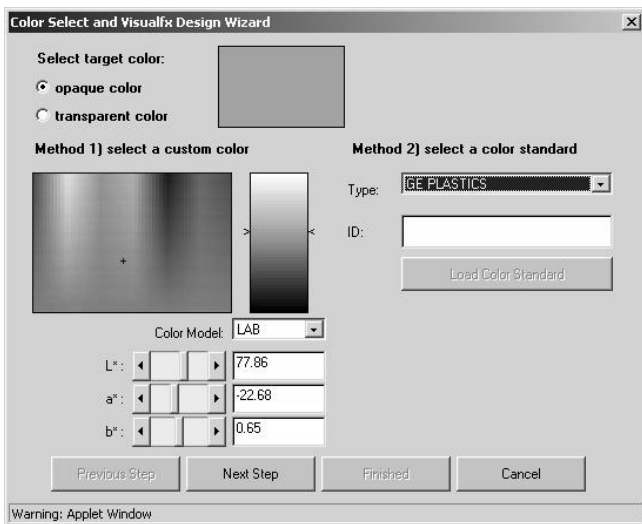
Figure 7: ColorXpress Select Web Page

In order to select a formula a customer first selects the resin type, opaque or transparent. Then they can select a custom color by specifying the color desired on the rainbow display or selecting a color standard by specifying the type and ID of the existing standard. If a point in the rainbow display is selected, the values of that point are placed in the numeric color value boxes. When the "Next Step" button is clicked the case selection algorithm will be executed and another screen will show the nine closest matches to the desired color. If a satisfactory match can not be found then a custom match request can be submitted and FormTool is used off-line to create the color formula. The formula created for the custom match will eventually be available on ColorXpress Select.

ColorXpress Select has been in use since 1999. It is one of the first customer service tools that GE Plastics has made available over the web. Tools like this have simplified the process for customers to submit orders over the web. GE now leads the plastic industry in on-line sales. The on-line dollar sales of GE Plastics are greater than the book sales of Amazon.com.

In 1998, the cost savings from FormTool and ColorXpress Select allowed GE Plastics to invest in another method for customers to select colors. In early 2000 GE Plastics opened a new $10 million ColorXpress center to help designers and marketers quickly create custom colors and special effects for plastics. The 4000 square foot center in Selkirk, N.Y. brings together all of the resources needed to select and develop custom colors and produce color chips, pellet samples, and prototype parts in a single day.

The idea behind the ColorXpress center is that in a competitive marketplace the color, texture, and style of a product can be a differentiating feature. An example of this is the Apple iMac computer. The ColorXpress center provides a location where customers can go through the CBR process of selecting a color face-to-face with a GE color matcher. The color matcher helps the customers refine the look and special effects of their products. This one-day service is only now available because of the FormTool system, which is the key tool used in the center. Before FormTool most color matches took over two days. Now, most matches take a day or less.

Figure 8: ColorXpress Center Chip Room

The case-base in the ColorXpress center is a color-chip room where three walls are filled with 20,000 baseball-card size colored plastic chips, see Figure 8. Three sets of overhead lights - incandescent, fluorescent and daylight – show the chips color varies under different lighting conditions.

Development included creating documentation, training manuals, tutorials, and submitting patents on various algorithms in FormTool. The U.S. Patent and Trademark office has granted GE four patents on various aspects of the color matching process described here.

- U.S. Patent No. 5,668,633; Method and System for Formulating a Color Match
- U.S. Patent No. 5,720,017; System and Method for Formulating a Color Match Using Color Keys
- U.S. Patent No. 5,740,078; Method and System for Determining Optimum Colorant Loading Using Merit Functions
- U.S. Patent No. 5,841,421; Method and System for Selecting a Previous Color Match from a Set of Previous Matches.

Maintenance

The FormTool case-base originally resided in a Microsoft Access database format and requires minimal maintenance. The main responsibility of the site experts was to update and backup the database and send new local cases for distribution to other sites using FormTool. The database is now in Oracle and this job is automated by having one global case-base.

New cases are automatically added to the database each time a color match is performed and saved. Filtering algorithms are run just before adding a new case to make sure that is in fact a non-redundant case. This has made it possible to keep the case-base database optimized as it grows with time.

Functionality has been built into the software to allow color specialists to add new pigments and dyes to the tool. This process involves producing a number of color batches used to characterize the optical properties of the pigment or dye that are then saved in the tool to be used in the case-adaptation algorithms. Additionally, the site expert has the responsibility to enter the rules for each pigment or dye. These rules include which product grade it can be used in and at what minimum and maximum concentrations. However, since new pigments or dyes are added infrequently, this does not consume much time of the color specialists. A visual basic maintenance tool was created to assist the site expert in these tasks.

Conclusion

FormTool is considered a huge success at General Electric due to the project's financial return on investment. It is also considered a technology achievement due to its early use of the CBR methodology, the number of patents obtained, and the opportunities for other systems it has created.

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