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SELECTION AND EVALUATION OF COLOR SCHEME FOR 4D CONSTRUCTION MODELS

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SUMMARY: *Four-dimensional models have proven to be an effective tool in construction management. The 3D models within these change color according to changes in the corresponding construction schedule. Color schemes play a crucial role in the design and representation of a 4D model. Good color schemes enhance an engineer's understanding of the situation at hand. Therefore, this research aims to develop effective and affordable tools for selecting and evaluating color schemes in 4D models. We proposed a two-step method of color selection. The first step is to determine the number of construction statuses and their relationships with each other. The second step is to select the colors to fit these statuses. In this research, we also developed three types of simulators to facilitate color evaluation. The display simulator is the first type of simulator developed and includes a LED monitor simulator, a projector simulator, and a printout simulator. The second type of simulator is the viewer simulator, which simulates protanopic blindness and tritanope blindness. The third type of simulator is the rendering simulator. This simulates the rendering results from the two major 3D viewers: NavisWorks and SmartPlant Review. Using the two-step selection method and the three types of simulators, we identified 21 color schemes (3 for 3 statuses, 12 for 5 statuses, and 6 for 6 statuses) ideal for presenting 4D models. We summarized our experiences by providing six guidelines for color selections. The color schemes and simulators were also implemented as a reference tool on a website (http://4Dcolor.caece.net). Future 4D model builders can refer to this website to select the color scheme that is most appropriate for their projects.*

KEYWORDS: *4D model, color scheme, selection, evaluation*

REFERENCE: *Ya-Hsin Chen, Meng-Han Tsai, Shih-Chung Kang, Chin-Wei Liu (2013) Selection and evaluation of color scheme for 4D construction models, Journal of Information Technology in Construction (ITcon), Vol. 18, pg. 1-19, http://www.itcon.org/2013/1*

1. INTRODUCTION

1.1 4D models

Four-dimensional models combine 3D models with a time schedule, and have been widely used for project planning and construction management. By using 4D models, engineers and stakeholders are able to visually explore construction activities and communicate more effectively. The added time schedule allows engineers to "scrub through" the duration of the project enabling them to foresee potential problems in construction progress and facilitate project management. Some Researchers found that 4D models can reduce model abstraction by linking 3D construction models to its schedule through associative relationships, as well as displaying more clearly the construction plan and the model's actual status (McKinney and Fischer 1998, Kuo et al. 2011). Koo and Fischer (2000) also found that 4D models can effectively integrate and display design and construction information, as well as promoting interaction and collaboration between team members within the project. Kim (2012) also indicated that 4D models can be a good tool for planning, analysis, and communication in civil engineering construction by carrying out a case study of a cable-stayed bridge project. These research results clearly show that 4D models are potential tool for construction management.

Previous studies have been based on the use of 4D models for different purposes in the project lifecycle. Many researchers have investigated the applicability of 4D models for site planning. Akinci et al. (2002) developed a tool that automatically generates site plans based on 4D models. Wang et al. (2004) extended the use of 4D technology into other related areas such as resource management and site space utilization. Dawood and Mallasi (2006) developed a tool named PECASO (patterns execution and critical analysis of site-space organization) to be used during site planning. Furthermore, some studies have developed 4D models for detecting spatial and temporal conflicts, as well as to understand construction logistics and demonstrate to the owners the planned progress (Tabesh and Staub-French 2006, Kam et al. 2003). Bosche and Hass (2008) proposed a 3D/4D CAD model with geo-referencing technologies for construction progress monitoring. Kubota and Mikami (2010) developed a 4D information management system to handle spatial and temporal information effectively, and verified its functionality by using actual data on road maintenance. These related works demonstrate that 4D models have multiple applications in construction management.

Some researchers have focused on the problems associated with the application of 4D models on actual constructions. According to the GSA (General Services Administration) building modeling guide series 04 (GSA 2009), 4D models can be used for the analysis of the temporal aspects of construction coordination and constructability review. Chang et al. (2012) used a 4D crane model to simulate site planning. Chau et al. (2004) implemented a 4D management approach to construction planning and site space utilization. Tsai et al. (2012)conducted a series of field studies to identify the benefits and problems of introducing 4D models in actual projects, discovering a vital issue regarding the application of 4D models, especially in large and complex projects (Dawood et al. 2002, Dawood et al. 2005). Tsai et al. (2010) developed a SUM (System Evaluation, Usability Study and Management Plan) framework to assist with the introduction of a 4D tool to a consulting firm. Hallberg and Tarandi (2011) used 4D models to present the life cycle information of a construction project and to analyze the different components of the building at different moments in time. Golparvar-Fard et al. (2009) presented a visualization model that integrates the 4D model and photographs within an augmented reality (AR) environment in order to allow for progress monitoring. Golparvar-Fard et al. (2011) and Yeh et al. (2012) also integrated a 4D/BIM as-built and as-planned model with AR as a tool for site management and construction maintenance. Nevertheless, with the increasing utilization of IT-based planning in the construction industry and, in particular, 4D modeling, the usability issue and effects of 4D modeling are becoming more noticeable and worthy of research.

1.2 Color schemes

Many researchers have noticed the impact of using colors in modeling for engineering purposes. Akinci et al. (2002) used particular colors to highlight spatial conflicts in a model and used them to notify users of constructability problems in their prototype system during time-space conflict analyses of construction sites. Song et al. (2003) suggested that a consistent application of colors would allow project performance metrics to be represented easily. Ahlstrom and Arend (2005) presented a prototype color palette that used color-coding to prioritize display information whilst maintaining good legibility in air traffic control displays. Gao et al. (2006) studied the importance of applying color drawings in construction, which facilitates designers and contractors with more efficient and accurate communication. This research indicates that, the selection of colors is an important consideration when developing 4D tools.

Four-dimensional models traditionally use color schemes to represent the corresponding construction status, with the schemes aiding engineers in visualizing the amount of progress that has been made. Dawood and Sikka (2008) noted that appropriate colors can be used as a tool to communicate more information to users. Puhalla (2008) pointed out that colors are an intrinsic attribute and the combination of various colors allows people to communicate visually to reinforce information hierarchy. However, the selection of the color schemes used currently is often based on engineers' personal preferences without considering the usability of these color schemes.

There have been many years of significant research into the question of how colors could be used to present information more effectively. Morgan (1995) believed that color was not simply an afterthought, but a potentially powerful means of conveying information by grouping or by drawing on a user's prior experience in encoding information. Zeng (2010) drew our attention towards the encoding of information through the use of color schemes in digital maps. Chen (2005) pointed out that usability is one of the ten unsolved problems in information visualization. Roh et al. (2011) proposed an object-based approach by using 2D or 3D charts with volume or color rendering. Plaisant (2005) reported that addressing the usability problem of information visualization needs a larger and more diverse group of users. Plaisant also indicated that using an appropriate color scheme would be necessary, providing an immediate benefit for users in applications. These results clearly show the need for usability tests in effective color presentations. In other words, rigorous usability tests may be beneficial in the selection of colors for 4D models.

Several studies have revealed that colors can affect the way users work and feel, and their personal experiences and mental state may affect their own perception of colors. A notable example of using colors to deliver information is the temperature world map, which is shown by Tufte (1997). Using unintuitive colors, which do not consider the relationship of information, may not be efficient or may even mislead. Ou (2004) concluded that colors may play different roles for different people in making decisions on what they like and dislike. The investigation in Lee et al. (2008) found that colors and shapes can affect the preference and feelings of 2D and 3D objects. Madden (2000) conducted a cross-culture study to indicate the relationships between cultures, color meanings, and color preferences.

The use of various colors simultaneously has also been documented. Cohen-Or (2006) presented a method for enhancing harmony amongst colors, which is aesthetically pleasing to human visual perception. Tokumaru (2002) developed a system to design and evaluate harmonic color schemes using fuzzy rules. At present, researchers have focused their study of color schemes on better integration in industrial practice. Harrower and Brewer (2003) proposed an online tool called ColorBrewer, which was designed to help cartographers select an effective color scheme for thematic maps. The Adobe Kuler system (Adobe 2008) is a web-based application developed for generating color schemes.

Evidently, color schemes have already been purposefully integrated into different kinds of engineering applications. A color scheme not only represents a set of attributes on a computer screen, but also acts as a cognitive tool linking information with a user's understandings. A well-chosen set of colors may assist users to process the information more effectively and efficiently. By considering the effects of color schemes, communication between engineers and engineering systems may also be improved.

1.3 Factors that may influence color schemes in 4D models

The usability of color schemes may be influenced by four main factors: data, device, viewer, and rendering algorithm.

The first factor is whether the color schemes are meaningful and intuitive in representing data. Rainbow colors are treated as the basic color scheme to visualize sequential data. However, Tufte (1997) indicated that the use of rainbow colors may sometimes misrepresent the nature of the data. Light and Bartlein (2004) pointed out that rainbow colors are not appropriate for representing sequential data. They revealed that when designing a data graphic, the relationships between the data should be considered in the selection of color schemes, which deliver information to users.

The second factor is that colors can be distorted while being shown on different display media, which may mislead engineer's interpretations of construction status. According to MacDonald (1999), the cause of this color distortion is that different kinds of display media, such as LCD monitors, projectors and printers, each have a different color gamut. To maintain color consistency, we refer to the standard defined by the International Color Consortium (ICC) (Fairchild 2005) and introduce the concept of color management. However, the concept of color management may not be suitable for the construction industry. It is difficult to require the wide variety of 4D users, including owners, engineers, construction managers, and subcontractors, to calibrate their devices solely to read the 4D model. For this reason, we must find a more robust color scheme, which can be displayed properly across different devices commonly used in the construction industry. The robust color scheme can convey the information correctly and serve as a good reference for making correct decisions more easily.

The third factor is the potential color vision deficiency of viewers. Research shows that about 8% of men and 0.4% of women have encountered color deficiency problems (MacDonald 1990, Tanaka 2010). Accommodating color deficiency into color selection can improve the usability of color schemes and applications. Many researchers have considered the usability of applications and implemented tools to design color schemes for color-blind viewers (Jenny 2007, Cui et al. 2008). In the field of civil engineering, the population is largely male, and thus accommodating color-blindness cannot be neglected. Another issue with the potential color is that most common color vision deficiency issues causes problems in distinguishing red and green colors (Ware 2004). These two colors are very commonly used by the researchers and engineers in the construction monitor to represent works as ahead or behind schedule (Bosche et al. 2008, Golparvar et al. 2009, Roh et al. 2011).

The final factor is the rendering algorithm that may influence the color schemes in 3D viewers and 4D models. Rheingans (2000) pointed out that three-dimensional visualizations impose different constraints than those in two-dimensional visualizations. Specifically, viewers use shading to judge the 3D shape of a representational object. Fitzhugh et al. (2009) conducted a study to establish effective 3D perspective interfaces. However, Forsyth and Ponce (2002) revealed that the rendering algorithms lead to a variety of complex shading effects, which is currently poorly understood and occurs widely. Therefore, to solve the influence of these factors, Chang et al. (2009) developed a systematic procedure to select color schemes for 4D models, called the SEUT (Selection, Examination, and User Test) procedure. Although the SEUT procedure can solve the usability problems of 4D models, the whole procedure is often too time consuming to be practical for regular developers or users of 4D models. In particular, following the procedure requires many hours to test the color schemes interactively. Each test involves real users and needs to set up the different use scenarios of 4D modeling, including projectors, LCD monitors and printers. Although SEUT is an ideal method to determine the colors for 4D models, it is still far from practical. The development of facilitating tools to reduce the procedure can be helpful. In particular, research, which can directly provide color suggestions to help users in the reduction of this procedure, is helpful.

1.4 Research objectives

One objective of this research is to develop a series of color schemes, which can maintain the usability, comprehensibility and consistency of 4D models under different use scenarios. The color schemes can ensure the proper presentation of the 4D models so that the users can clearly and easily interpret the information from the model. The other objective is to develop simulators to simulate different user scenarios for 4D users. These can be also used to facilitate color selection processes. In particular, three simulators will be developed in this research. The first simulator validates the influence caused by different software with different graphical algorithms. The second simulator is to test the inevitable color distortions caused by different devices, such as projectors, LCD monitors and printers. The third simulator visualizes the view of color blindness, as approximately 8% of the male population suffers from color deficiency. The research results, including the validated color schemes and simulators will be published on the Internet as a reference for future 4D modelers.

2. RESEARCH METHOD

In this research, we first proposed a two-step method for color selection. After color selection, we selected effective color schemes that served as the visual metaphor for construction statuses. Next, we developed three simulators to evaluate the color schemes in color evaluation. Using the simulators, it was possible to grasp the trend of the color distortions and determine effective color schemes for 4D models. Color selection and evaluation is an integration of color scheme determination. If a color scheme cannot pass the color evaluation examination, it should be reselected in the color selection. After selecting and evaluating color schemes in 4D models, we accomplished three major results. Figure 1 shows the framework for selecting and evaluating color schemes for 4D models.

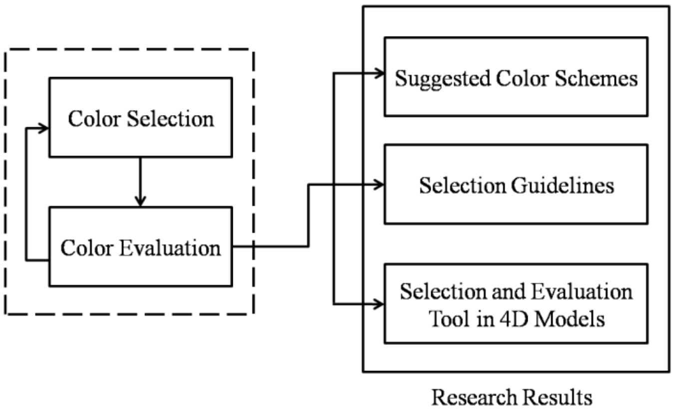


FIG 1. Framework for selecting and evaluating color schemes for 4D models

The color selection method can generally be classified into two steps. We first determined the application purposes and the number of statuses by analyzing the information that 4D models deliver. After analysis of the 4D models, we determined the relationships between statuses and found corresponding colors for each status in the second step. Performing this two-step method in color selection, effective color schemes for 4D models were selected according to schedule information.

We conducted color evaluation to examine the distinctiveness of color schemes under different viewing situations. The color evaluation had three types of simulators: a rendering simulator, a display simulator and a viewer simulator. The rendering simulator provided the results of color schemes with different rendering algorithms. The second simulator is the display simulator and simulated a view of color schemes when displayed on display media. The viewer simulator was the final simulator and examined whether color schemes are distinguishable for colorblindness in color deficient vision.

After going through the integration of color schemes determination, three major research results were identified. A suggested color scheme was selected by considering the needs of 4D models and evaluating the usability of different color schemes, thereby reducing users' time in selecting color schemes for their 4D models. A web-based tool was developed for users to assess the suggested color schemes and the simulations of color schemes in different scenarios. The selection guidelines summarized our experience in selecting and evaluating color schemes for 4D models, which can help users in selecting their own color schemes more efficiently. The following sections will introduce the details of each part of the research method.

3. COLOR SELECTION

To select ideal color schemes for 4D models, we proposed a two-step method for selecting color schemes that can efficiently improve engineers' understanding of the construction progress. For the purpose of selecting effective and intuitive color schemes, the first step was to determine the application purposes of the 4D models and its number of statuses. In the second step, we determined the relationships between statuses and the corresponding colors to represent each status. After following the principle of color selection in color schemes, we selected the respective schedule information of construction. The following sections will discuss the details of each step in color selection.

Step 1: Determine the application purposes and the number of statuses

Colors were displayed sequentially to represent the schedule information of construction progress, which may vary according to different purposes. As a result, the usability requirements of 4D models should be identified before selecting color schemes. The information from the time schedule can first be categorized into two factors: the application purposes and the number of construction statuses. Considering both of these two factors, we can determine the usability requirements to implement in 4D models.

The purpose of each application had different objectives and needs. After analyzing the 4D models, the key aspects of the application purposes can be summarized into two main objectives: project planning and construction management. For the purpose of project planning, the 4D models were used to predict potential interruptions between different activities to reorganize the sequence of activities. In order to figure out potential interruptions in the proper sequence of works before a project starts, the color schemes may clearly and efficiently deliver schedule information, allowing engineers to foresee potential problems before making decisions. On the other hand, for the purpose of construction management, 4D models were required to show contemporary situations of construction activities. As a result, 4D modelers were asked especially to pay detailed attention to the delay-group whenever a delay of construction activities occurred. In order to manage the construction's progress, 4D models should coordinate subcontractors and activities during construction. When 4D models were used to compare the actual schedule against the planned schedule, this helped engineers to better understand and control the project's progress.

The number of construction statuses plays an important role in color selection. The use of 4D models in construction planning and management vary with the number of statuses. The number of statuses varies with different purposes and different levels of information detail depending on the specific information the engineers would like to emphasize. For instance, the typical planning of 4D models may have three statuses: (1) pre-construction, (2) under construction, and (3) completion. Another example typical of 4D models for managing six statuses: (1) pre-construction, (2) under construction, (3) completion, (4) pre-construction delay, (5) under-construction delay, and (6) completion delay. To confirm the baseline of construction activities, engineers check the finish-group to plan the next step of their project using activity labels such as finished, finished ahead of schedule and finished within schedule. The projects referred to in the literature review and the interviews with engineers appeared to have 3, 5, or 6 statuses that we used to categorize the projects (Benjaoran and Bhokha 2009, Liao et al. 2007). We then selected appropriate number of colors to represent the corresponding construction statuses.

Step 2: Determine relationships between statuses and corresponding colors

After determining the application purposes and the number of construction statuses, we selected color schemes to match the construction statuses. The details for selecting effective color schemes for representing the schedule information are described below.

According to the relationships between constructions statuses, we can select effective color schemes to be fitted to visualize schedule information. In this research, we adopted diverging and sequential data to select our color schemes, following the ideas and data investigated by Harrower and Brewer (2003). We also proposed the inclusion of an additional data type, i.e. independent data. The use of independent data is similar to the pair schemes used in Harrower and Brewer's research. It presents the colors for construction tasks, which have a relationship but are not in an explicitly ordered relationship. Figure 2 shows examples of using sequential color, diverging color and independent color. After selecting appropriate color schemes based on the construction stages, the effect of the display can then be simulated by using ICC profiles. Each ICC profile contains the parameters related to the feature of the display.

Data type	**Sequential data**	**Diverging data**	**Independent data**
Color scheme			
Construction stages	Pre-construction Under-construction Completion	Pre-construction (Structure department) Under-construction (Structure department) Completion (Structure department) Pre-construction (Pipeline department) Under-construction (Pipeline department) Completion (Pipeline department)	Pre-construction Under-construction Completion (emphasize) Pre-construction delay Under-construction delay Completion delay

FIG 2. Example of using sequential color, diverging color and independent color

Each type of data has its unique purpose. Independent data was used to represent more than two types of data to emphasize a special class, which may be the basic hues of color schemes. Diverging data had two types of data and was used when a critical break point was to be emphasized. Finally, sequential data is suited for representing data that ranges from low-to-high values. Based on the basic hues, sequential colors were selected for representing sequential data. A classic example of this is the use of color to show corresponding temperature.

In this research, we used sequential colors, which imply a specific order or sequence to represent the order of construction activities. In project management, some of the statuses have "delay" situations, which should brought to the viewers' close attention. We selected warm colors, known as aware colors, to indicate the delay statuses, such as pre-construction delay, under-construction delay, and completion delay. On the other hand, cool colors were used to represent the safe and stable on-going status of activities.

Color scheme selection was performed on a calibrated monitor (Dell E248WFPb), which is calibrated by Datacolor Spyder 3 Pro. We adopted the method reported by McDonald (1999), which is one of the more practical ways of selecting harmonious color schemes. Since users often watch 4D models for a long time, we adopted harmonious color, schemes which were less strenuous on the users' eyes. This method indicated that we could first select a basic color according to the number of statuses in the 2D hue circle then, following the specific relationships to select other colors, create a set of basic hue colors. For example, if we want to select a two-hue color scheme for management, we needed two basic colors to represent the on-going group and the delay-group. In this case, we use red to represent the delay-group. Since we needed two basic colors, we chose a dyad-complementary relationship between the colors, with green as our complimentary color. In addition, we varied the colors in lightness and colorfulness to create sequential color schemes, making the color schemes more diverse.

We avoided using warm colors in the plan because the construction statuses do not need as much awareness management. Sequential color schemes had been used to explain the start-to-finish relationships between construction statuses. Some 4D models have three kinds of completion statuses, which allow engineers to learn more details of the construction status to arrange resources. These three completion statuses can be both regarded as independent data and sequential data of each other. Therefore, combinations of sequential, independent, and diverging data were created.

On the other hand, project management requires delay statuses to be emphasized. For this purpose, warm or aware colors are used to represent the delayed statuses. These colors include red, yellow, and orange. The research reported that viewers seemed to be attracted by vivid colors. The completion status is an important part of project control especially the communication of the completion of activities to managers. As a result, the completion status may be independent. Therefore, these three types of data were identified for management.

4. COLOR EVALUATION

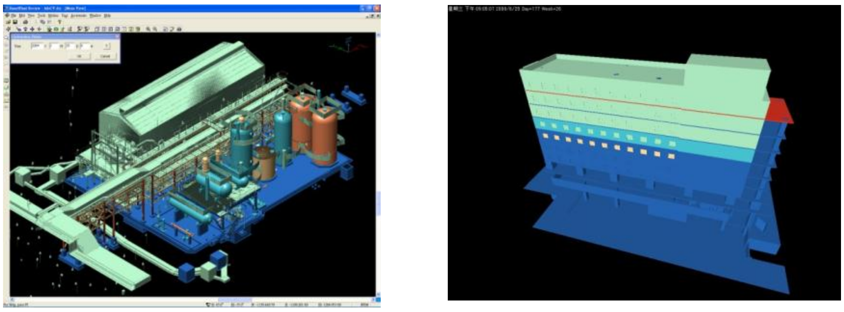
To evaluate the color schemes obtained from color selection, we simulated the effects of color schemes displayed in color evaluation. We provided three types of simulators for the evaluation to help engineers examine whether the color schemes are distinguishable under different situations. The three types of simulators we developed in this research were the rendering simulator, the display simulator, and the viewer simulator. In the following sections, we will introduce the details of each simulator.

4.1 The rendering simulator

The rendering simulator was used to examine the usability of color schemes with different rendering algorithms in 3D viewers. Three-dimensional visualizations were used, each having different constraints from two-dimensional visualization. Specifically, viewers use shading to identify 3D shapes of a representational object. Shading the calculated shape by rendering algorithms may cause color distortions in visualizations. This effect may strongly influence the color schemes of individual elements. Different 3D viewers were considered to solve this problem. However, the rendering algorithms varied in different 3D viewers, causing the shading of color schemes to be unpredictable.

Two well-known and common 3D viewers were considered in this research, Bentley Intergraph SmartPlant Review and Autodesk NavisWorks. The main reason we chose these two programs is that Bentley and Autodesk are two major solution providers in the current industry. Many ongoing projects use these tools to visualize the construction processes. The other reason is that their rendering algorithms have a noticeable difference. We believe choosing them can represent most users' experiences of using 4D models.

The color schemes selected in our color selection were pasted into this simulator and applied in the 3D viewers. As shown in Figure 3, even a color scheme with the same color values render differently in SmartPlant Review and in NavisWorks. The results simulated by the rendering simulator in NavisWorks were more vivid than the colors in SmartPlant Review. This is especially apparent for the color red. This effect may influence the distinctiveness of color schemes.



(a) (b)

FIG 3. The color scheme implemented in different applications: (a) SmartPlant Review; (b) NavisWorks

4.2 The display simulator

The display simulator can simulate the influence of display media. In using 4D models as a means of communication, we may use different display media to present to the user, such as a LCD monitor, projector and color printouts. However, the display capacity of each device is different, causing color inconsistency. The lights of the display environment also influence the presentation of colors and the interpretation of 4D models. By using the display simulator, we examined the color schemes and realized the trend of color distortion with different display media and two kinds of environment: lights-on and lights-off.

To simulate the effect of the influence of display media, we used ICC profiles to retrieve the color information of various display media. The process of creating an ICC profile is shown in Figure 4. Computers first output a set of original color values to display media, allowing the display media to display the colors, called output targets. When the display media then reproduced the original color values with the limitation of their color gamut, the original color values may distort. A colorimeter is an instrument used for measuring light. We measured the color values of output targets with a colorimeter and compared the original color value by calculating variations between the two data. After calculating the variations, the color information of the device was estimated and an ICC profile was created by recording the colorimeter's measurements.

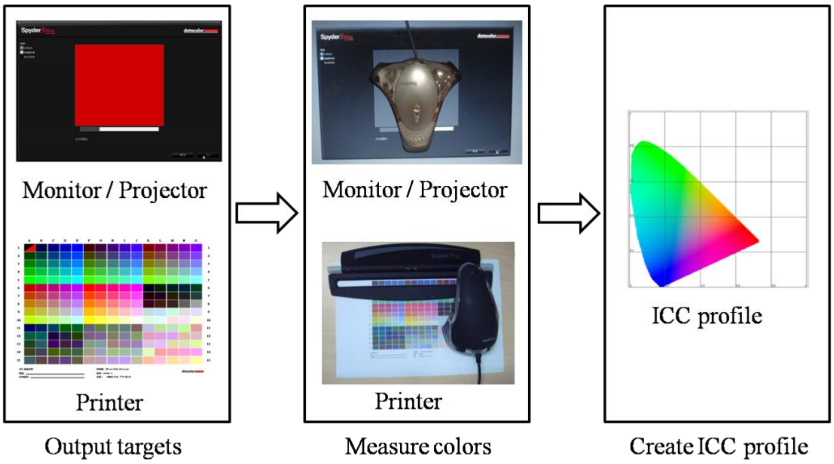


FIG 4. Process of creating an ICC profile

Monitors, projectors and printers are the more common forms of display media for presentations, and were thus considered in this research. Before simulating the effects of display media, we tested the color gamut of each display media. The devices we tested are listed in Table 1. The color gamut of each display media was significantly different. Comparing the different devices, the slight distortions caused were less significant.

TABLE 1: Tested devices for color gamut

Type of Display Media	**Display Media Device**		
LCD monitor	Dell E248WFPb	ASUS VH232H	
Projector	Hitachi CP-A100	ViewSonic PJ656	Mitsubishi Electric XD500U-ST
Printer	HP ColorLaserJet 3800dn	HP ColorLaserJet 2840 PCL6	Epson aculaser C2600

In order to simulate the effects of the display media, one device of each display media was selected. The devices we selected for each type of display media were the Dell E248WFPb to represent LCD monitors, the Hitachi CP-A100 to represent projectors, and the HP ColorLaserJet 3800dn to represent color printers. The color gamuts of the three devices are shown in Figure 5. As the figure shows, the LCD monitor has the largest range of color gamut, with the projector and the color printout having completely different capacities for displaying colors.

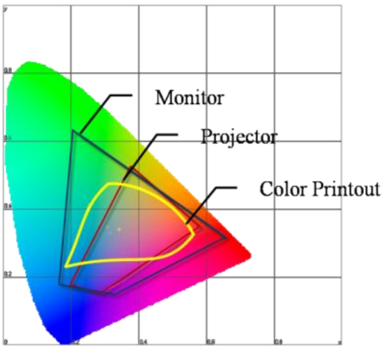
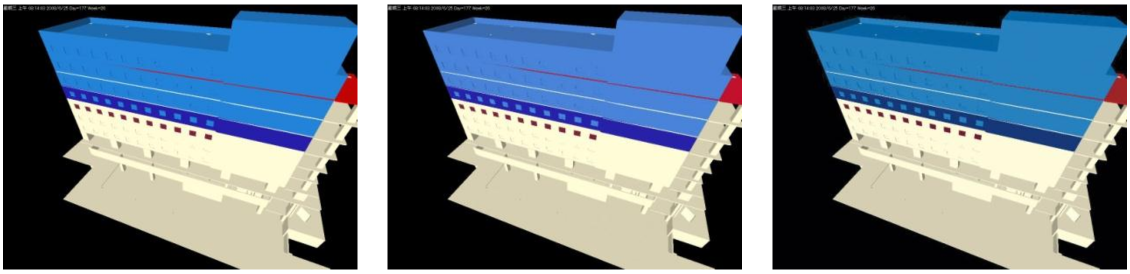


FIG 5. Color gamut of display media

The mapping allowed a choice between the closest possible color match and remapping of the entire color range for the different gamuts, followed by the occurrence of color distortions. By converting the original color gamut into the display media's color gamut with their ICC profile, colors were mapped to their possible positions. Finally, the results of color schemes shown on display media were simulated in the display simulator.

We used the display simulator to examine the color distortions of different media. One of the color schemes we selected using the display simulator is shown in Figure 6. The results showed that the same color schemes displayed on different media are still similar although the color printout was slightly darker than the others were.



(a) (b) (c)

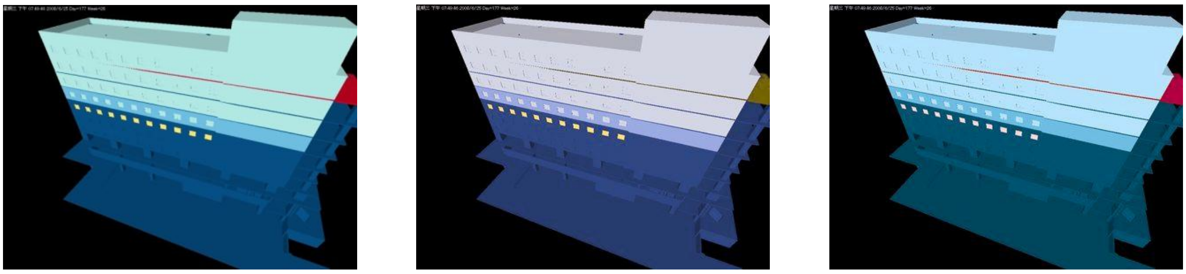
FIG 6. Results of (a) monitor, (b) projector, and (c) color printout using display simulator.

4.3 The viewer simulator

The viewer simulator attempts to solve the color distinctiveness problem for all viewers. Distinguishable color schemes are an important issue in using 4D models for communication. Colors are not always distinguishable by all people. Thus, we used the viewer simulator to examine the distinctiveness of color schemes among normal people and those with color deficiency.

In this research, we considered two common types of color blindness, protanopia/deuteranopia and tritanope. Protanopia is a lack of red cones and deuteranopia is a lack of green cones. People with these deficiencies are unable to distinguish colors of the green-yellow-red section in the spectrum. People with tritanope cannot distinguish the yellow-blue section in the spectrum. To simulate the visions of protanopia and tritanope, we used the images captured from the rendering simulator. By generating the computer-simulated images, we examine the effect of color blindness. We simulated protanopiatic and tritanopic vision using the simulation algorithm published by Brettel et al. (1997). In particular, we tested our color schemes using the web tool "Vischeck" (www.vischeck.com) by Dougherty (2002), which implements the algorithms of Brettel et al. We uploaded the images of each color scheme to "Vischeck" and examined the problems of colorblind vision with regard to indistinguishable color.

Figure 7 shows the results of simulating color blindness. In colorblindness, red and green become different degrees of yellow or brown. Therefore, in this research, we selected blues with reds in our color scheme rather than greens to avoid any color deficiency problems. The results of our simulations revealed that this strategy of selecting color schemes appeared to yield very positive results.



(a) (b) (c)

FIG 7. Simulation of colorblindness: (a) normal vision, and (b) protanopia / deuteranopia vision (c) tritanope vision

5. DEVELOPMENT OF COLOR SCHEMES

In this research, we interactively test the colors using the simulators and work closely with industrial partners. 21 color schemes were determined and suggested to the users of 4D models. The following section describes the details of this development.

5.1 Search for the ideal color schemes

After we determined the schemes of colors in section 3 and developed the simulators for examining colors in section 4, we then started to investigate the ideal color schemes for 4D models. This is the most time-consuming work in this research. We started randomly selecting the combinations of the colors and tested them in the simulators. We then gradually found some implicit rules behind the selection processes. In this section, we organized the basic procedure of selecting colors, and the following sections will describe involving industrial participants in the decision-making circle to ensure the color is appropriate in practice. We will then describe the guidelines organized from our experiences.

First, we selected a color scheme with a different hue. For example, we selected green, blue, and yellow sequential colors to represent color schemes A, B and C. In order to select colors to represent diverging data, we adopted the dyad-complementary relationship and selected two basic hues. Next, we selected sequential colors based on their basic hues. If the data was sequential-independent data used to emphasize completion status, we then adopted a triad-primary relationship and selected three basic hues.

Finally, 21 suggested color schemes were selected, as shown in Table 2. We also listed the details of the 21 suggested color schemes in Figure 8. Users can use this information to apply the color schemes easily in their 3D viewers.

Table 2. 21 suggested color schemes for 4D models

Application purpose	No. of statuses	Construction statuses	Color set
Planning	3	Pre-construction Under-construction Completion	A, B, C
	5	Pre-construction Under-construction Completion Just-completed Completion before schedule	D, E, F
	5	Pre-construction Under-construction Completion (Emphasize) Just-completed Completion before schedule	G, H, I
Management	5	Pre-construction Under-construction Completion Pre-construction delay Completion delay	J, K, L
	5	Pre-construction Under-construction Completion (Emphasize) Pre-construction delay Under-construction delay	M, N, O
	6	Pre-construction Under-construction Completion Pre-construction delay Under-construction delay Completion delay	P, Q, R

Set ID		RGB			HTML color code	Set ID		RGB			HTML color code	Set ID		RGB			HTML color code
A						**B**						**C**					
A1		247	238	203	F7EECB	B1		167	219	216	A7DBD8	C1		205	229	196	CDE5C4
A2		247	217	109	F7D96D	B2		48	182	183	30B6B7	C2		135	157	111	879D6F
A3		250	179	80	FAB350	B3		49	130	189	3182BD	C3		49	99	49	316331
D						**E**						**F**					
D1		188	189	220	BCBDDC	E1		223	194	125	DFC27D	F1		235	247	185	EBF7B9
D2		117	107	177	756BB1	E2		166	97	26	A6611A	F2		252	228	71	FCE447
D3		224	228	204	E0E4CC	E3		33	124	204	217CCC	F3		178	226	226	B2E2E2
D4		135	157	111	879D6F	E4		128	205	193	80CDC1	F4		188	189	220	BCBDDC
D5		64	134	106	40866A	E5		1	133	113	018571	F5		117	107	177	756BB1
G						**H**						**I**					
G1		0	186	254	00BAFE	H1		223	194	125	DFC27D	I1		235	247	185	EBF7B9
G2		28	114	183	1C72B7	H2		166	97	26	A6611A	I2		252	228	71	FCE447
G3		205	229	196	CDE5C4	H3		184	225	134	B8E186	I3		188	189	220	BCBDDC
G4		135	157	111	316331	H4		44	162	95	2CA25F	I4		117	107	177	756BB1
G5		49	99	49	316331	H5		0	94	37	005E25	I5		95	68	130	5F4482
J						**K**						**L**					
J1		184	225	134	B8E186	K1		116	169	207	74A9CF	L1		0	186	254	00BAFE
J2		77	172	38	4DAC26	K2		5	112	176	0570B0	L2		28	114	183	1C72B7
J3		247	247	247	F7F7F7	K3		254	217	142	FED98E	L3		179	202	198	B3CAC6
J4		241	182	218	F1B6DA	K4		65	9	54	400936	L4		161	16	62	A1103E
J5		208	28	139	D01C8B	K5		164	11	84	A40B54	L5		222	4	4	DE0404
M						**N**						**O**					
M1		167	219	216	A7DBD8	N1		161	218	180	A1DAB4	O1		158	202	225	9ECAE1
M2		48	182	183	30B6B7	N2		65	182	196	41B6C4	O2		109	148	200	6D94C8
M3		49	130	189	3182BD	N3		34	94	168	225EA8	O3		8	81	156	08519C
M4		241	182	218	F1B6DA	N4		253	204	138	FDCC8A	O4		250	105	0	FA6900
M5		222	4	4	DE0404	N5		251	48	31	FB301F	O5		202	0	32	CA0020
P						Q						R					
P1		161	218	180	A3D9B4	Q1		167	219	216	A7DBD8	R1		33	124	204	241BA2
P2		65	182	196	41B6C4	Q2		49	130	189	3182BD	R2		36	27	162	217CCC
P3		34	94	168	225EA8	Q3		233	233	233	E9E9E9	R3		247	238	203	F7EECB
P4		253	204	138	FDCC8A	Q4		247	217	100	F7D964	R4		222	4	4	DE0404
P5		252	141	89	FC8D59	Q5		252	83	27	FC531B	R5		191	13	70	BF0D46
P6		251	48	31	FB301F	Q6		202	0	32	CA0020	R6		120	30	58	781E3A
S						T						U					
S1		188	183	123	BCB77B	T1		167	219	216	A7DBD8	U1		167	219	216	A7DBD8
S2		135	157	111	889E6F	T2		104	180	213	68B4DB	U2		104	180	213	68B4DB
S3		64	134	106	4A876A	T3		5	75	126	054B7E	U3		5	75	126	054B7E
S4		247	217	109	F7D96D	T4		247	217	100	F7D964	U4		241	182	218	F1B6DA
S5		255	146	89	FF9259	T5		252	83	27	FC531B	U5		208	28	139	D01C8B
S6		250	105	0	FA6900	T6		202	0	32	CA0020	U6		202	0	32	CA0020

FIG 8. Detailed information of 21 suggested color schemes

5.2 Participation of industrial partners

During the research, we iteratively consulted with the industrial partners to ensure the usability of the proposed color scheme. To be more specific, we held two official meetings to gather participants with multiple backgrounds from the industry. All the practitioners work in design-build companies. Their main projects contain planning processes, designing models and construction management in each stage of the life cycle of the project. All practitioners have 5 years modeling experience.

The first meeting was held at the midpoint of the research. Its main goal was to collect opinions about the color schemes we suggested by displaying them through the simulators. Three experienced engineers and two managers participated at this meeting. In the meeting, we tested the color schemes under different models and light conditions. Detailed parameters are shown in Figure 9.

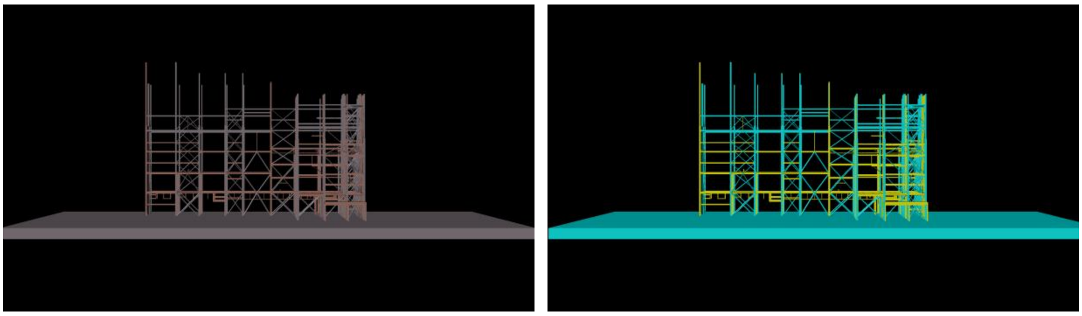


FIG 9. Color schemes proposed in the meeting with construction partners

There were two major suggestions: (1) the colors need to be principal colors, such as red, green, blue, and so on; (2) the colors need to be vivid (saturated). The two suggestions were considered and we decided to change the rules of color selection. We first determined the common colors used in the site, such as red, green, blue, yellow, and so on (Golparvar-Fard et al. 2007, Golparvar-Fard et al. 2009). By slightly offsetting the colors, we attempted to find colors that were similar to principal colors but avoided confusing colors for color deficiency reasons. The other change was trying not to choose the consist colors to display in all media. We selected the colors that can be distinguished and that conveyed correct information across each media. In other words, we shifted the focus from minimizing the color distortion to the correctness of color interpretation across different media.

The second meeting was held to validate the finally determined color schemes. Detailed information of these color schemes can be found in Figure 8. All the color schemes had passed examination through the three simulators (rendering, display and viewer simulator). We invited the industrial participants to this meeting, explaining the 21 suggested color schemes on varied 4D models across different media. We found that the industrial participants could easily interpret the meaning behind the 4D model. For example, users were able to understand a temporal order of construction status by presenting it as a sequential color scheme; similarly, warm colors like yellow, orange or red draw viewers' attention easily when presenting delay situations. From the positive feedback of participants, we gained confidence to use these colors on the 4D model.

In short, in this research, we iteratively used the simulators and invited industrial partners to help verify the colors. From thousands of combination of colors, this process helped identify 21 color schemes useful for the 4D model. The 21 color schemes considered use scenarios across varied environments, media and users, as well as the customary practice in the construction industry.

6. SELECTION GUIDELINES FOR 4D MODELERS

After having developed the color schemes, 4D color selectors and the evaluator, we summarized our experiences and delivered guidelines for future reference. These guidelines can greatly help 4D modelers to select their own color scheme reducing the lengthy trial-and-error process.

The deviated selection rule is ideal for color deficiency in 4D models: By following the rules for color schemes selection, the results showed that this rule was generally useful after processing through the color evaluator. At the color scheme selection step, 21 color schemes were chosen. After the color evaluator generated these schemes, we found 21 of these color schemes were still distinguishable; the other four colors schemes were either unsuitable for distinguishing or unsuitable for the colorblind.

Blue-red and yellow-purple combinations work well on display media and for colorblindness: The results of the simulations (display media and colorblindness) showed that the combinations of blue-red and yellow-purple color schemes have little color distortion and remain significantly distinguishable in the 4D model.

A yellow-orange-red color scheme is effective for representing delay statuses: From our experience of selecting color schemes, we found difficulty in selecting sequential colors for red, which are used to represent delay statuses. Therefore, we used a yellow-orange-red color scheme to represent delay statuses. In addition, we found that this color scheme works well for color deficient vision.

Avoid using green colors in project management: Because we used warm colors to represent the delay status, green colors should be avoided when representing on-going status to fulfill the needs for colorblind users.

Avoid using green, red, and yellow together: In color deficient vision, these colors may be too similar and indistinguishable. For example, green and red may look like dark shades of brown, which may be viewed as very similar to yellow.

Yellows should be avoided as the middle status of construction management: During the process of simulating colorblindness vision, we found it inappropriate to use yellows in the middle class of independent data to emphasize the critical or break point, for example, the completion status in the 5 statuses of management. The reason is that colorblindness easily blends a yellow middle class into the reds creating confusion for the users.

7. SELECTION AND EVALUATION TOOL FOR 4D MODELS

We also developed a tool to facilitate the process of selecting and evaluating the 21 colors schemes we suggested. This tool is available on a website titled *4D Color Selector and Evaluator* (http://4Dcolor.caece.net), showing the results of 21 suggested color schemes from this research.

This web-based tool has a main window to show what the color schemes look like on 4D models under different simulators. Around the main window, there are some functions for color selection and color evaluation. This website has two main functions: selection and evaluation. In the color selector, we provided 21 suggested color schemes for the users. The users can then choose the color scheme that fits best with their needs depending on the number of construction statuses. The color evaluator contains the three types of simulators (the rendering simulator, the display simulator, and the viewer simulator) mentioned earlier. Users can see the simulations, without needing to apply it into 3D viewers or showing it on different display media. A time-control bar below the main window allows users to control the speed and direction of the 4D model video, such as playing forwards, backwards, and pausing. The interface of *4D Color Selector and Evaluator* is shown in Figure 10.

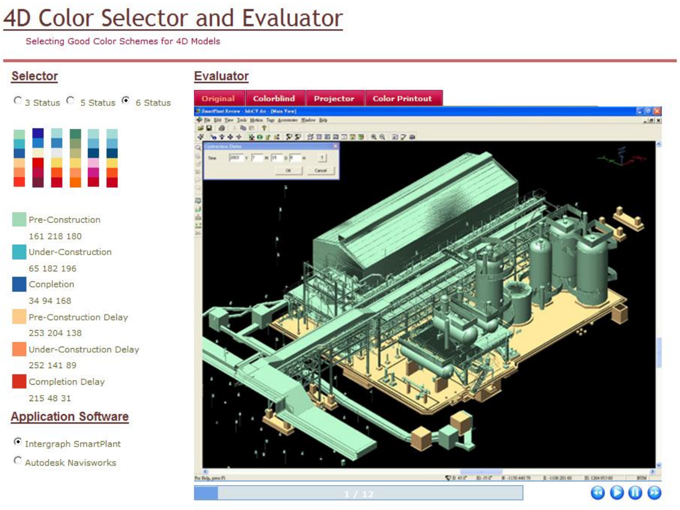
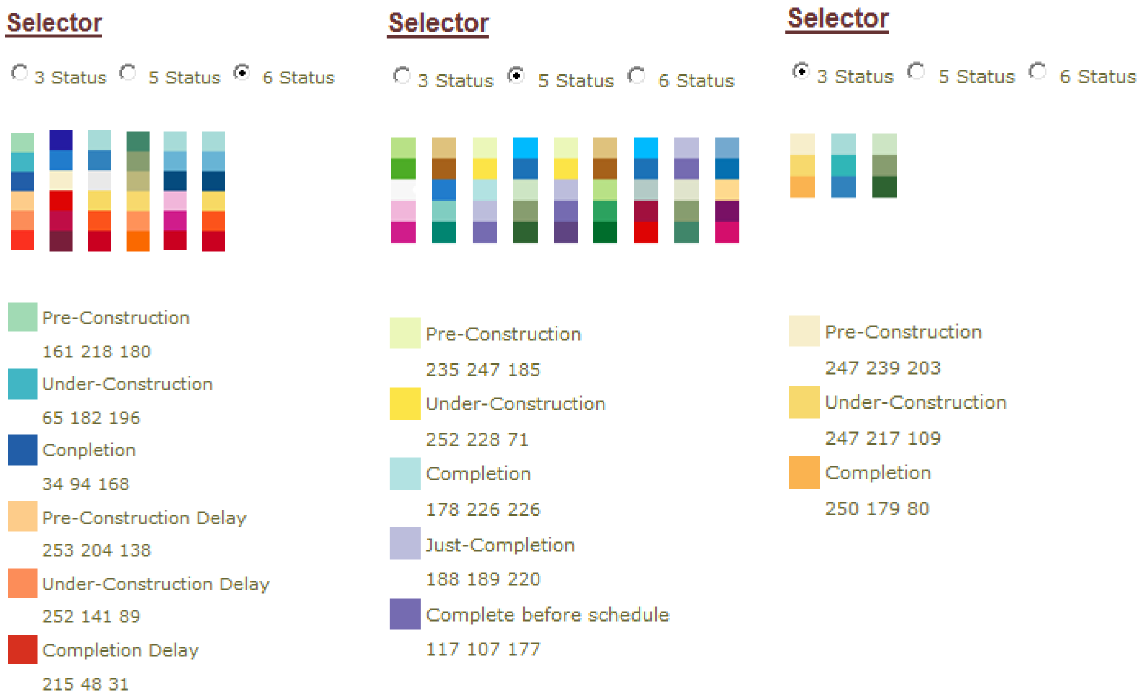


FIG 10. Tool for selection and evaluation of color scheme in a 4D model, 4D Color Selector and Evaluator

The function of the color selector allows users to select a color scheme depending on the number of construction statuses. The tool provides three different amounts of statuses: 3 statuses, 5 statuses and 6 statuses. Users can choose the one that will fulfill their needs best by clicking on the corresponding radio buttons. After clicking the radio button, the color selector will show some suggested color schemes below it. The suggested color schemes are selected by considering the application purposes and the relationships between construction statuses. When users click on a color scheme, the color selector then shows the details of the color scheme. The details include the explanations and the RGB value of each color. The user interface of the color selector is shown in Figure 11. By providing RGB values, users can conveniently apply the color scheme in their application software. When users change their options, the user interface also changes.



(a) (b) (c)

FIG 11. User interface of color selector

The main window shows how the color scheme looks in the application. The 4D models show the sequential change of colors. To achieve this, 12 images were captured from different time points in the 4D models in the application software. The website provides two common applications: Intergraph SmartPlant Review and Autodesk NavisWorks. Image-based 4D models were combined by using those sequential images, thereby reducing the loading of 4D models.

The evaluator in the web-based tool allows users to visualize their color schemes under different conditions. This tool provides the results simulated by the three types of simulators. The three basic types of display media are simulated by the display simulator. Above the main window are the simulations under different situations. The simulations include: original, projector, color printout, protanopic blindness, and deuteranopic blindness. Creating a 4D simulation often works well with monitors. As a result, images being displayed on a monitor were regarded as original simulated images. The simulation provided by the color evaluator allows users to understand the color distortions of different display media thereby helping them in their color scheme decision.

8. Discussion and Contributions

8.1 Discussion for color selection

We provided 21 well-tested colors schemes, as well as a selection and evaluation tool, as references for construction practice. Future 4D modelers and users can choose a color scheme that fits their purposes well and can test them on the Internet. This reduces tremendous time and effort.

In this research, we found very different requirements from planners and managers. The planners required fewer colors. They only needed to show the on-going tasks, completed tasks and future tasks. However, managers need to handle greater complexity. The colors used range up to six, in order to adequately present the site condition. They were especially interested in the "problematic" group, such as delay tasks or the tasks to be delayed. In our research, we used warm colors to represent the problematic group. This helps the manager identify the problem more easily.

From the process of selecting color, we found that it is tricky to find the sequential red colors. Red cannot be presented well especially on the projector, as it looks more like brown. Therefore, we consequently combined orange and yellow to present the different severity of the delay.

We also found that the color blindness simulator is the main constraint when selecting colors. Therefore, we tried to avoid the non-green hues because it looks similar to red for users with color blindness. We also tried to implement the deviated selection rule, which deviated from the dyad-complementary relationship in color selection. As a result, we selected blue-red color schemes instead of green-red color schemes. Using this method, we can increase the possibility of passing the viewer simulator. Using this color scheme, those with protanopia color blindness can read the colors and interpret the 4D models as normal people do.

8.2 Research Contributions

In this research, the main contributions can be summarized as follows:

We developed 21 suggested color schemes. They are fully tested, avoiding the confusion caused by different types of displays and rendering algorithms. Difficulties in the interpretation of the colors by those who suffer from color blindness are also avoided. 4D modelers and users can directly use the colors by referring to Figure 8.

The color schemes convey the "meaning" behind the 4D models. Since 4D models are often used to present the construction sequence, we include sequential colors in the suggested color scheme. We also selected diverse colors to distinguish normal tasks from delayed tasks. The implications of colors serve a hint to enhance the comprehensibility of the model.

A web-tool was developed for use on the Internet. It demonstrates the 21 color schemes on different 4D models. It also simulates the color distortion due to the displayer, software and even the color deficiency of the viewers. The colors can be shown on different 4D models. This allows the users to fully test these colors and decide the most suitable schemes for their purpose.

This research provides a scientific approach for selecting the colors for 4D models. We do not treat the selection of colors as personal preferences or an act of art. Instead, we carefully selected the colors to ensure that their interpretation can be correct and require less mental effort. Because of the rapid development of BIM, the 4D simulations can become more popular. The color schemes can be widely applied and eventually provide benefits to the industry.

Compared with Chang et al. (2009), which presents the latest research for colors of 4D/BIM models, this research is much closer to the practical requirements. Although SEUT can also identify color schemes, it is far from being applied in actual sites. By using simulators and suggested color schemes, this research has solved the problem by reducing as much as 90% of time required by the SEUT method.

9. CONCLUSION

The major contribution of this research is the reduction in time and effort in determining appropriate color schemes of 4D models. To achieve this, we developed three simulators: (1) a rendering simulator to simulate the rendering results from different software, (2) a display simulator to simulate the 4D models displayed on projectors, LCD monitors and printouts, and (3) a viewer simulator to simulate the vision of color blindness. We used these simulators to evaluate a large number of color schemes and finally define 21 color sets suitable for 4D models. Three of them can be applied in 4D models with 3 construction statuses. They could be used to present future tasks, ongoing tasks and completed tasks, respectively. Twelve of them can be applied in 4D models with 5 construction statuses. Six of them can be applied in 4D models with 6 construction statuses. We summarized our experience of defining the color schemes and developed them as a guideline for the users who would like to customize their own colors. We finally created a web-based tool to allow engineers to view 4D models by assigning different color schemes and simulation scenarios. This can help users efficiently evaluate and select appropriate colors for 4D models.

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