PTIMIZATION FOR ENHANCING COLLABORATIVE DESIGN

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ABSTRACT

A computerized model, CoED (Collaboration Enhancing among Design participants) was developed, focusing on the relationships between designers, design variables and design phases. It uses optimization, based on Genetic Algorithm, to decompose these relationships into workgroups of relevant designers and design issues, for each design phase. It identifies intersecting issues between designers, allowing them to be aware of the effects of their decisions on issues relevant to others and enlightening tradeoff options for each one so that conflicts may be avoided and controlled. CoED takes into account the way different designers regard design variables, and it's change through the design process, after decisions have been made. This supports a circular process, which is a more appropriate procedure for design.

KEYWORDS

Optimization, collaborative design, design process.

INTRODUCTION

It is customary to present the design process as a linear continuous progression of different design phases, in which design variables discussed (Shaviv and Kalay 1992). In the process, the group of active participants changes to include designers from different professions in different design phases (Kalay et. al. 1998). This means that there are designers who are no longer a part of the team, while others had not yet joined.

One of the major problems of a multi-disciplinary design is the possibility of conflicts. Conflicts can rise from the linear phases of the design, where decisions made in early phases by the active designers of that time, affect design variables and decisions to be made by participants in later phases. Conflicts may also rise from opposing demands by designers of different professions. These designers relate to different variables, have different jargon and approach the project from different points of view. This makes it difficult to relate to the needs of other designers and to understand the effect of one's decisions on their work (Wiezel & Becker, 1992). Not only designers of different professions regard variables and their relationships differently, but also designers of the same profession may consider them differently' based on their experience and beliefs.

Much research has been done in collaborative design. Design tools were developed, many of them evaluate design solutions created in advanced, detailed phases of the process (Fazio & Bedard 1992, Pohl et. al. 1992, Muhdavi et. al. 1997, Anumba et. al. 2002, Caldas & Norford 2002). Several models focused on management and organizing, attempting to create better communication between designers, dealing with the problems of database and connecting numerous designers with it (Augenbroe 1995, Kim et. al. 1997, Papamichael et. al. 1997, Morozumi et. al. 2002). Other models tried to redefine the design data and the work process, so that it will relate to the views of different professions (Gross et. al. 1998, Jeng & Eastman 1998, Kalay et. al. 1998).

All these models deal with different aspects of collaborative design. Nevertheless, only few of them actually relate to the problem of conflicts. Minimal conflict resolution is done either in a knowledge-based system or by using a predetermined priority list.

In a regular design process, conflicts are identified after decisions have been made, and conflict resolution is often made in a zero-sum approach (one wins and one loses). We believe that win-win solutions can be achieved, if intersecting issues, where conflicts may rise, are discussed in time, and if tradeoffs with other variables can be found.

Our work suggests a different approach. We present a new model CoED that focuses on the relationships between designers, design variables and design phases. It uses optimization to divide these relationships into groups and creates a design process that fits the specific group of designers. Other optimized groups of relationships allow each participant to be aware of the effects of his decisions on other issues of the design, together with a full set of tradeoff options for a specific issue. In this paper, we present CoED and discuss the way optimization may be used to enhance collaboration in the design process.

THE MODEL

The main goal of the work was to examine the way different designers regard design variables and their relationships, during the different design phases and to use these relationships to enhance the collaboration between the participants, in order to achieve better design solutions (Figure 1).

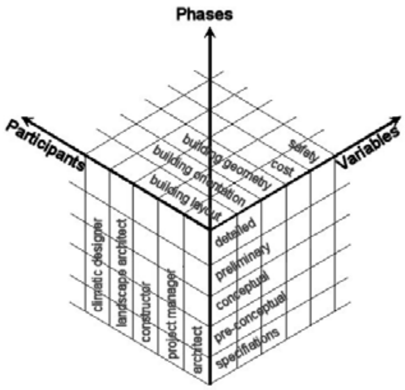

Figure 1 A 3D matrix presenting the relationships between design participants, variables and phases.

CoED was developed with the purpose of revealing the following information to each participant in each design phase:

1. Who one should consult with (other designers),
2. When (in what design phase),
3. What about (which design variables).

This information will allow the participants to identify the intersecting issues, where conflicts may rise. Complementary information will help resolving conflicts:

- The identification of possible tradeoffs for design variables for each participant.
- The list of designers related to a specific design variable.
- A discussion group of designers and the relevant design variables, from a specific tradeoff group for one designer, or a group of designers.

This information is helpful to all the participants, and should be provided to them from their own point of view. That way, the designers will be able to know when they affect other designer's work.

Another goal was to develop an open and flexible model that can be easily adjusted to each project. This is an important feature, since different projects may include different design variables, and different participants in the design teams, each of them has his own opinion regarding the variables. Present day simulation models are often restricted to simulate subsystems. The current philosophy is to give the different consultants the choice to use their own preferable simulation tools. CoED combines all the designers with their simulation subsystems, so that conflicting demands can be avoided or resolved. In this way CoED is not restricted to specific tools. The design process using CoED becomes an efficient procedure where simulation and evaluation tools are used effectively by each designer in order to improve the design of the building. Figure 2 presents the design process using CoED, and the way various simulation tools may be used in it.

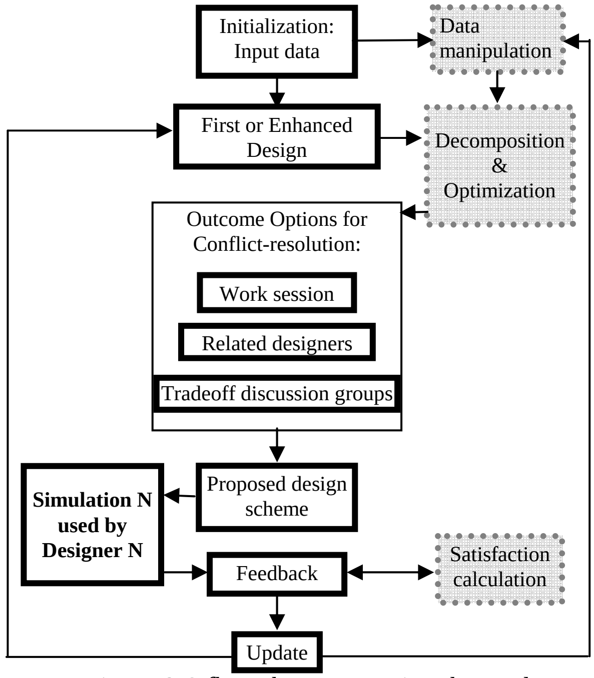

Figure 2 A flow chart presenting the work process using CoED, and the way the designers combine their familiar simulation tools in the design development. Dotted lines presents internal processes by CoED.

Input data

CoED considers data based on the opinions of a defined group of participants, and arranges them in relationships matrices. It includes a list of all participants that will take part in the design group at any time, the opinions of each participant regarding the importance of different design variables, and the effect of each variable on other variables. The data is obtained from the design manager (usually the architect), and from the specific group of participants. At the beginning of each project, the design manager enters the complete list of participants, then each one of them enters:

- The importance of each design variable to his work on a scale of 0-2 (0 is irrelevant and 2 is very important),
- The effect of each design variable on the discussed variable, on a scale of 0-2 (0 indicates no effect while 2 indicates that the discussed variable is highly affected by another variable).

CoED organizes the data in three types of matrices, according to the specific information:

1. The effects of project constraints on the design variables (a matrix for each designer) (Figure 3),

2. The relationships between design variables (a matrix for each designer) (Figure 4),
3. The importance of each design variable for the designers (one matrix for the project) (Figure 5).

The matrices presented here are part of a particular case study that was conducted to examine CoED.

		Topography	climate	winds	view	regulations	Building area	context	Exist.elements
		1	**2**	**2**	**1**	**1**	**1**	**2**	**2**
Build. orientation	**2**	2	2	2	2	1	1	2	2
Space orientation	**2**	1	2	2	2	0	0	1	1
Layout	**2**	2	2	1	1	2	2	1	1
Space organizing	**1**	0	2	2	1	0	1	1	1
Interior design	**1**	0	2	2	1	0	1	1	1
Space geometry	**1**	1	1	2	1	0	0	0	0
Build. geometry	**2**	2	2	2	2	2	2	2	2
Envelope area	**1**	0	2	2	0	0	1	0	1
Window area	**2**	0	2	2	2	1	1	1	1
Window location	**2**	0	2	2	2	0	0	1	1
.	.	.	.	.	.	.	.	.	.

Figure 3 Part of a basic relationships matrix of constraints (columns) and design variables,(lines) relevant for a climatic designer. Highlighted numbers are importance values she assigned to constraints and variables. The full matrix is 8X20.

		Build. orientation	Space orientation	Layout	Space organizing	Interior design	Space geometry	Build. geometry	.
		2	**2**	**2**	**1**	**1**	**1**	**2**	.
Build. orientation	**2**	-	2	1	0	1	0	1	.
Space orientation	**2**	1	-	1	1	1	1	1	.
Layout	**2**	2	1	-	1	0	1	2	.
Space organizing	**1**	2	2	1	-	1	1	1	.
Interior design	**1**	2	2	1	1	-	1	1	.
Space geometry	**1**	2	2	1	1	2	-	1	.
.	.	.	.	.	.	.	.	.	-

Figure 4 Part of a basic relationships matrix between variables relevant to a climatic designer, importance values highlighted. This matrix is 20 X 20.

	Architect	Acoustics	Climate	Constructor	Electrician	HVAC	Installation	Landscape	Lighting	Project Manag
Build. orientation	1	2	2	0	0	2	1	2	2	0
Space orientation	1	1	2	0	0	2	1	1	2	0
Layout	2	2	2	1	0	1	2	2	0	2
Space organizing	2	2	1	0	1	2	2	0	1	0
Interior design	1	0	1	1	1	0	1	0	2	0
Ground floor area	1	0	0	0	0	2	1	2	1	2
Circulation	1	0	0	0	0	2	0	2	1	1
Space area	1	1	0	1	0	2	0	1	2	1
Space height	1	1	0	2	1	2	0	0	2	2
Space geometry	1	0	1	2	1	2	0	2	2	1
Build. geometry	1	2	2	2	0	2	0	1	0	2
Envelope area	2	0	1	1	0	2	0	0	2	1
Window area	1	2	2	1	0	2	0	0	2	2
.	.	.	.	.	.	.	.	.	.	.

Figure 5 Part of a basic relationships matrix between designers and variables. Matrix is 10X35, including all variables and participants of the project.

Data manipulation

The basic matrices represent the subjective opinions of the designers. The model processes them in order to reflect some objective factors that affect the importance of the variables and their relationships.

<u>Symmetry of relationships</u>

The designers are used to think of the design process in a linear way, according to the design phases. In many cases, designers will point out the effect of variables discussed in early phases on those discussed later on, but not the other way around; we claim that the relationship between two design variables can be reversed. For instance, the size of a window is affected by its orientation, which is an early variable. However, if the size of the windows must be predetermined, it may affect their orientation. CoED calculates the values for the symmetry as the sum of the two values presenting the effects of each variable on the other (an example shown in figure 6).

<u>Flexibility of a variable</u>

A variable which is more flexible will be less important, because it can be changed easily. It will also be a good tradeoff candidate for other variables it is related to. Moreover, usually the designers do not take into account the change of importance along the process. This is crucial since there is great reluctance for changing design variables that has alredy been decided.

Therefore, the weighted importance of each design variable is calculated to include not only the assigned importance by the designer, but also:

1. the degree of rigidity – that represents the progression of the process. At the beginning, the rigidity of all variables is 0, which means they will be determined in the "future". Variables discussed at "present" are half-rigid, and variables that were already decided in the "past" are 100% rigid since the tendency is not to change them if possible. This means that the importance of each design variable is changed during the design process, according to whether some decisions have already been taken for them.

2. the degree of constraints – that represents the effect of constraints on the variable. The more constraints affect the variable, the less flexible it is, hence more important.

3. the degree of tradeoffs – that represents the number of relationships associated with the variable. The larger the degree of tradeoff the lower the importance of that variable.

Nevertheless, if a designer assigned a variable the value of 0 (irrelevant), the weighted importance will be 0 as well. The model disregards such a variable for that designer, and the variable will not appear in his matrices. The variable will appear in the project matrix of designers and variable but with the value of 0 for that designer (as can be seen in Figure 5).

Figure 6 presents part of the matrix shown in figure 4 as a symmetrical matrix with the weighed importance of each variable.

		Build. orientation	Space orientation	Layout	Space organizing	Interior design	Space geometry	Build. geometry	.
Build. orientation	**111**	-	3	3	2	3	2	3	.
Space orientation	**95**	3	-	2	3	3	3	3	.
Layout	**113**	3	2	-	2	1	2	4	.
Space organizing	**57**	2	3	2	-	2	2	2	.
Interior design	**54**	3	3	1	2	-	3	2	.
Space geometry	**36**	2	3	2	2	3	-	2	.
Build. geometry	**122**	3	3	4	2	2	2	-	.
.	.	.	.	.	.	.	.	.	-

Figure 6 Part of a symmetrical matrix of relationships between variables, for a climatic designer and the calculated weighted importance (shown in bold). The full matrix is 20 X 20.

Flexibility of relationships

The weighted importance of the variables affects their relationships. The more important the variables are, the higher their relationship value should be (Figure 7). However, if one of the two variables is more rigid, its value as a tradeoff candidate is lower, and the relationship value will represent it.

The "relationship between design variables" matrices will be used for creating tradeoffs posibilities by decomposition. Therefore, the higher the relationship value, the more likely the two variables will be assigned to the same tradeoff group.

		Build. orientation	Space orientation	Layout	Space organizing	Interior design	Space geometry	Build. geometry	.
Build. orientation	**111**	-	506	524	368	465	347	533	.
Space orientation	**95**	506	-	408	452	449	431	517	.
Layout	**113**	524	408	-	370	267	349	635	.
Space organizing	**57**	368	452	370	-	311	293	379	.
Interior design	**54**	465	449	267	311	-	390	376	.
Space geometry	**36**	347	431	349	293	390	-	358	.
Build. geometry	**122**	533	517	635	379	376	358	-	.
.	.	.	.	.	.	.	.	.	-

Figure 7 Part of a final matrix of relationships between variables, for a climatic designer, including calculated weighted importance (shown in bold) and weighed relationship values. Full matrix is 20 X 20.

Value of participants

The "relationship between designers and variables" matrix is also updated to include the weighed values of importance for each participant. This matrix is intended to be used for creating workgroups. For this purpose, the importance of each designer in the specific project is included. For example, in most projects the acoustic designer will be assigned with medium importance. Nevertheless, if the project is an opera house, his importance value will be very high, consequently, variables that are important to him will have high importance value in the matrix (Figure 8).

	Architect	Acoustics	Climate	Constructor	Electritian	HVAC	Installation	Landscape	Lighting	Project Manag.
	5	**10**	**4**	**4**	**2**	**2**	**2**	**4**	**3**	**5**
Build. orientation	385	760	444	0	0	182	148	492	288	0
Space orientation	320	190	380	0	0	176	112	320	270	0
Layout	610	760	452	308	0	110	220	508	0	770
Space organizing	550	880	228	0	148	200	220	0	159	0
Interior design	295	0	216	200	88	0	70	0	225	0
Ground floor area	395	0	0	0	0	206	98	380	84	545
Circulation	305	0	0	0	0	192	0	384	153	420
Space area	210	400	0	324	0	194	0	284	192	335
Space height	180	400	0	396	76	192	0	0	228	400
Space geometry	290	0	144	412	82	192	0	436	222	270
Build. geometry	290	1030	488	448	0	196	0	236	0	740
Envelope area	610	0	220	184	0	208	0	0	234	415
Window area	295	720	412	224	0	242	0	0	207	640
.	.	.	.	.	.	.	.	.	.	.

Figure 8 Part of designers and variables matrix, taking into account the importance of the designers (in bold). The full matrix was 10X35.

Relevance of variables

During the design process, after a variable has been discussed in a meeting, it is less relevant to the participants of that meeting. Therefore, each discussed variable is divided by a relevance coefficient to lower its values, but only for the participants that attended the meeting. This is done so that this variable could be discussed again in different contexts.

Algorithm for decomposition

Decompositions are carried out in order to identify the participants that should meet in each design phase and the issues they should discuss in each meeting. Other decompositions create the groups of variables for tradeoff. All decompositions are created by Genetic Algorithm (GA), an optimization method that is based on evolution principles found in nature (Holland 1975). Each optimized decomposition gives us the groups with higher values of connection within them, and minimal connections between them.

The algorithm in CoED relates to principles discussed in previous works on genetic algorithms such as selection (Goldberg and Deb 1991), control and survival (Syswerda 1991), population control (Krishnakumar 1989). It combines them with other principles found in nature that were not processed into numeric methods before, such as sexual reproduction. In this kind of reproduction, each individual has pairs of chromosomes it inherits from both parents, and the phenotype (the seen characteristics) of the individual is created according to rules of dominance. In this context, the mating of two individuals cannot be done by crossing-over alone, but by creating reproduction "cells" through a process called meiosis. This process divides the pairs of chromosomes into single chromosomes, using crossing-over between them to mix the genes from the parents. The new individuals simply inherit single chromosomes from both parents. This option gives higher divergence and reduces the need for other control methods such as "mutation", which have their limitations (Goldberg 1989, Tate & Smith 1993).

In CoED, each individual is the coded presentation of a possible decomposition, according to the kind of matrix it is performed on. Since the algorithm should perform different decompositions of different characteristics, and since we wanted to maintain the option of variables and designers belonging to more than one group, the individual encoding was too complicated for a single chromosome. Therefore, the use of pairs of chromosomes was developed. There are three pairs of chromosomes in each individual as follows:

1. A chromosome that is responsible for the control of the number of groups (this chromosome is not active in the meeting groups decomposition).
2. A chromosome that is responsible for assigning variables to groups.
3. A chromosome that is responsible for assigning designers to groups (this chromosome is not active in the tradeoff decomposition).

The performance value is calculated by three factors:

1. A general performance, which is the ratio between the values that are connected in the groups and the disconnected ones.
2. The performance of each group, which is the percentage of the high values in the group subtracting the percentage of the zero values in the group.
3. The disconnection factor, which takes into account the relationships that were not assigned into groups, and checks their values. Lower values mean an improved individual.

The outcome of the model

The information presented to the designers is based on the results obtained by the decompositions. There are three types of information:

1. Work groups

The workgroups consist of the most relevant issues (design variables) that should be addressed at a specific time in the design process, together with the designers that should discuss them. It is the result of a decomposition of the "relationship between designers and variables matrix" (as presented in Figure 8). The workgroup meetings best fit a specific design group in a certain project, since it is based on their subjective views (an example shown in Figure 9). These meetings replace the common design phases.

Meeting 1

Designers	Variables
Project manager	General layout
Architect	Building layout
Constructor	Building geometry
Climatic designer	Envelope materials
Landscape architect	Structure
	Structure materials
	Finish materials (outdoors)

Meeting 2

Designers	Variables
Project manager	ground floor area
Architect	safety
Landscape arch.	circulation

Climatic designer	Building orientation
Lighting designer	Vegetation
	Area shading
	Spaces orientation

Meeting 3

Designers	Variables
Project manager	window area
Architect	window materials
Climatic designer	window shading
Lighting designer	Finish materials (indoors)
Acoustics designer	

Figure 9 The first three work sessions that best fit a partial group of designers. In meeting 2, there are two sequential meetings. In this case, designers in bold are those attending both meetings.

2. A list of all designers related to a design variable

This list is obtained directly from the designers and variables matrix (as presented in Figure 8).

3. Groups of possible tradeoffs for a design variable

The tradeoff groups include variables that are closely related to a specific variable, and strongly connected between them. These groups are exclusive for each designer, since they are based on their opinions. They are obtained from decompositions of the "relationships between design variables matrix" of each designer (as presented in Figure 7). The tradeoff groups may assist the designers both in dealing with possible conflicts with other designers during the design meetings, and in handling possible internal conflicts they may encounter during their own work.

Identifying tradeoff groups is important because the participants tend to miss connections when searching for tradeoffs, although they defined the one-to-one relationships to start with. An example of this aspect is shown for one designer. A climatic designer was asked to identify groups of closely related variables from the list of the design variables she regarded as relevant to her work. Then the performance value that indicates the quality of the decomposition was calculated. The groups created by the designer are shown graphically on Figure 10. As one can see, it was incomplete as not all the important relationships were divided into groups (lines crossing between groups), which means that not all possible tradeoffs were identified. Moreover, some groups included many weak relationships (light lines), but cut off closely related variables (dark lines).

On the other hand, the decomposition created by CoED (Figure 11) showed that all important relationships are grouped together; therefore, all possible tradeoffs are available for use.

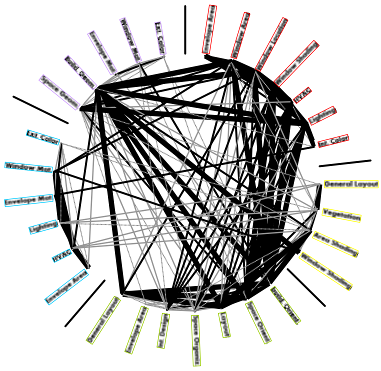

Figure 10 The groups of tradeoff created manually by the climatic designer. Each group is shown by different color. The performance value is 45%.

Figure 11 The groups of tradeoff for a climatic designer created by CoED by performing decomposition. Each group is shown by different color. The performance value is 88.9%.

Decision-making

The decision making process is based on the importance values of both design variables and designers, and thus create a method of presenting the degree of satisfaction of each designer for a suggested design scheme. The degree of satisfaction is calculated from the feedback of the designers regarding the scheme. Each designer gives feedback to all design variables relevant to the scheme (Figure 12). It is then processed to create scheme satisfaction graphs for each designer, based on the importance values of the variables (Figure 13), and for all the designers, based on the importance of each designer (Figure 14). The all-designers graph also presents a minimal satisfaction value each designer should achieve based on his importance. Satisfaction value that is lower than this value means that the scheme does not meet a minimal performance for that designer. The more important the designer is, the higher his satisfaction should be. The feedback graphs are presented to the architect (or project manager) who makes the decisions.

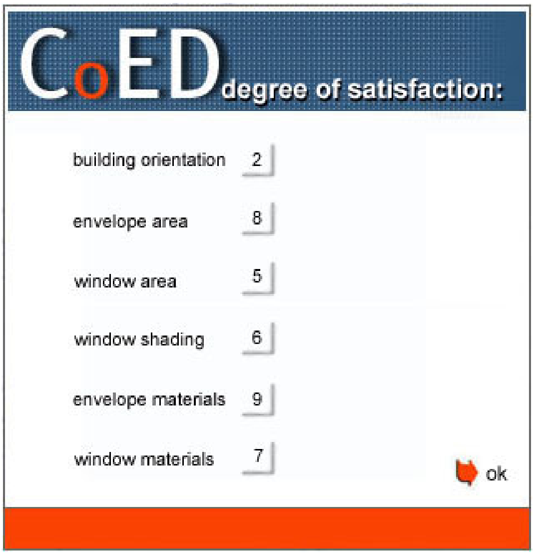

Figure12 Satisfaction Table for a specific design scheme. The scale of values range from 0 to 10

SUMMARY AND CONCLUSIONS

The design process created by CoED presents a series of design meetings, composed of the designers and the design variables related to them. Each meeting consists of the most relevant group of designers and variables for the specific timeline. In this design process, the design variables that are most important to the designers are discussed in early phases, while less important design variables are discussed in later phases. In the same way, the important designers attend more meetings than others. Some of the design variables are discussed more than once, with different groups of designers. This happens when the design variable is closely related to many different issues, and when many designers consider it important.

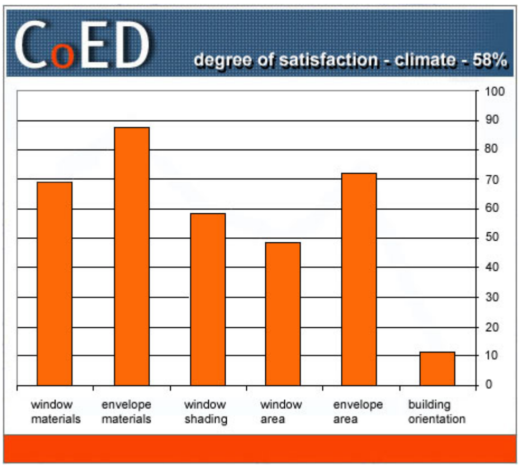

Figure 13 A satisfaction graph, calculated from the satisfaction table shown in Fig.12, with the importance of each variable. The total value of the scheme for this designer is on the head of the graph.

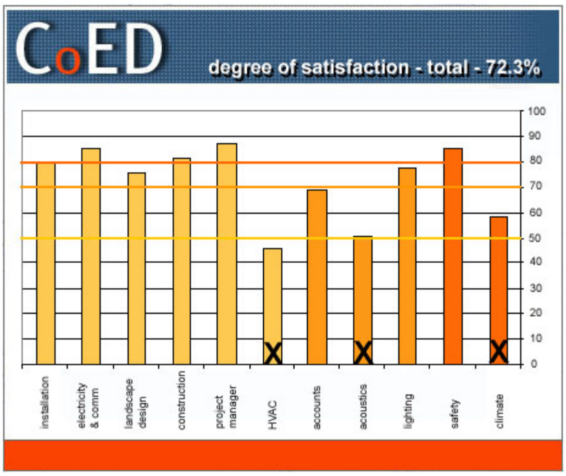

Figure14 Satisfaction graph of all designers: Overall satisfaction value shown on the header. Darkness indicates designer importance: darker color means higher importance. Horizontal lines in the same darkness represent minimal required values . X labels represent unsatisfied designers with score lower than the required minimum

CoED's design process is completely different than the linear one (see tables 1 and 2). The regular linear approach of collaborative design presents a top-down process, in which the design develops from schematic to detailed solution. This approach is characterized by a predetermined progression of a process, in which the order of discussing different variables is constant, and the designers join in a more or less customary sequence. On the other hand, the process according to CoED combines the top-down approach with a bottom-up, in which the whole is also created by its details. It is more suitable for design as most designers tend to work in a circular way, in which they regard different design variables several times, each time in a different perspective (Shaviv and Kalay 1992; Chase 2002). CoED creates groups of design variables that include different aspects of the same issue: functional, geometrical, materials etc. (a combination of general and detailed aspects), and determines the related designers. This allows a group of designers to discuss many aspects of a specific issue that is relevant to all of them. It means that the designers join the process according to the issues discussed, so they participate in decisions made for each relevant variable. Moreover, conflicting demands for a certain variable may surface during these meetings and be resolved on the spot by viewing other aspects of that issue. Table 3 presents the differences between the customary design process and the one created by CoED.

CoED enhances collaboration between designers, each using his own methods, habits and simulation codes, rather than by trying to integrate the simulation codes and by creating one data base.

Table 1 The customary design phases in which design variables are discussed.

Phase	Issue	Variables
Pre-conceptual	Context	Layout, circulation
	Geometry	Ground floor area, building geometry
Conceptual	Context	Buiding orientation
	Geometry	Space area, envelope area, window area
	Organization	Space allocation
Preliminary	Context	Landscape design, space orienation
	Geometry	Space height, space geometry, w. shading
	Organization	Interior design
	Structure	Structure
	Systems	Installation
	Materials	Structure materials, envelope materials
Detailed	General	Safety
	Context	Vegetation, area shading
	Geometry	Safety elements
	Systems	HVAC, elec. & comm., lighting, fire
	Materials	Windows materials, finish materials,color

Table 2 The first 4 phases created by CoED, and the design variables discussed in them. The variables in parentheses are discussed a second time.

Meeting	Issue	Variables
1	Context	Landscape, layout
	Geometry	Building geometry
	Structure	Structure
	Materials	Structure mat. Envelope mat. Out. finish
2	General	Safety
	Context	Build. orientation, space orientation, area shading, vegetation, circulation
	Geometry	Groun floor area
3	Geometry	Window area, window shading
	Materials	Window materials, indoor finish
4	General	Cost, (safety)
	Context	(landscape design), topography
	Geometry	(building geometry), space geometry
	Structure	(structure)
	Materials	Out. finish

Table 3 Differences between customary design process and CoED.

Issue	CoED	Customary process
Meeting schedules	Determined according to relevant variables at the time, based on previous meetings.	Scheduled according to customary design phases, experience and opinions of the design manager.
Multi-participants meetings	Variables for discussion are relevant to all attending designers. In other cases, parallel groups are defined.	Periodical meeting is scheduled for the design team of that phase. There are variables which are irrelevant to some designers, and often the outcome of the meeting is unsatisfactory.
Conflicts	Work groups focus the designers on the relevant issues. In these meetings possible conflicts will rise in a controlled environment.	Many conflicts rise from incompatible demands, and exposed in later phases as problems caused by earlier decisions.
Conflict resolution	Conflicts are resolved creatively by using tradeoff groups each of the designers can obtain for every variable.	Conflict resolution is made by the more powerful designer, or by the progress of the design, since early decisions are rarely changed.

The suggested approach is aimed to assist in preventing possible conflicts that are quite common in the regular design process. The model developed is taking a different point of view from previous models: it deals with the relationships between the designers and the design variables, and the effect of the progression of the design process on these relationships. It also takes into account the different opinions each of the designers might hold, whether they are from different professions or not, and even if the designer changes his positions in different projects. The model uses optimization to create a new design process, which supports a circular design process. It illuminates the intersecting issues between the designers, and identifies possible tradeoffs thus creating a controlled environment to deal with possible conflicts. This information assists the designers in finding creative solutions without the need to compromise.

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