Improved Link Analysis Method for User Interface Design—Modified Link Table and Optimization-based Algorithm

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Abstract

Link analysis is one of most wildly used methods in user interface design to arrange control elements on user interfaces. However, traditional link analysis method is insufficient for evaluating transitional cost associated with accessibility (the easiness for the operator to reach certain control element on the interface) and the link table commonly used contains no directional information for assessing difficulty. To address these two problems, an improved link analysis method based on a modified link table and a branch-and-bound algorithm is proposed in this study. A case study on a simplified control interface of a boiling water reactor (BWR) in a real-world nuclear control system was exemplified to elucidate the improved method and an experiment was conducted to validate the effectiveness of the method in improving users' performance time. The results showed that the total completion time and the completion time of accessibility-associated operations were significantly shorter on the interface modified by the improved method than by the traditional link analysis method, while the difference of the completion time of proximity-associated operations between the two interfaces was non-significant. Therefore, although the traditional link analysis method can significantly ameliorate the random interface by optimizing the proximity between control elements, the improved method can further improve the total completion time by optimally trading-off the accessibility and proximity. The method can be applied to the interface which requires physical movements between the user and the interface and within the interface, especially touch screen and control panels.

Keywords: Link Analysis, Interface Design, Accessibility, Optimization

1. Introduction

Link analysis (LA) is a quantitative and objective method for examining the relationships between interface components, which can be used for optimizing component arrangements (Wickens *et al.* 2004). It aims to improve interface design by examining the task content, the characteristics of each individual component on the interface, and the relationships between them. The cost of each operation in the task is quantified by a link value, and the link value can be a function of importance, frequency, distance, difficulty or other characteristics of the movement between two elements. The goal of link analysis is therefore to minimize the "overall cost" by rearranging the layout while the operator uses the target interface under certain task requirements.

Traditional link analysis method uses a link table or a link diagram to represent 'links' between interface components. Figure 1 shows a link diagram of an in-car radio, and Table 1 shows its link table. Each movement between interface components is represented by a straight line. For example, to eject the cassette requires the user to push button A, and then button F. But some "one-touch" operations, such as pushing button H only to reverse the play, may be considered neither in the link diagram nor in the link table. In addition, only half of the link table is used so that operations of different sequence (A →F/ F→A) cannot be distinguished in the table (and F→A obviously does not make sense). Finally, the link value represents how many movements between two components should be done by finishing one run of all tasks. Based on the link table, traditional link analysis would improve the interface by minimizing the length of existed links on the interface. Figure 2 shows one possible improved interface layout by traditional link analysis method. Basically, the proximity of all linked elements should be improved by shortening links.

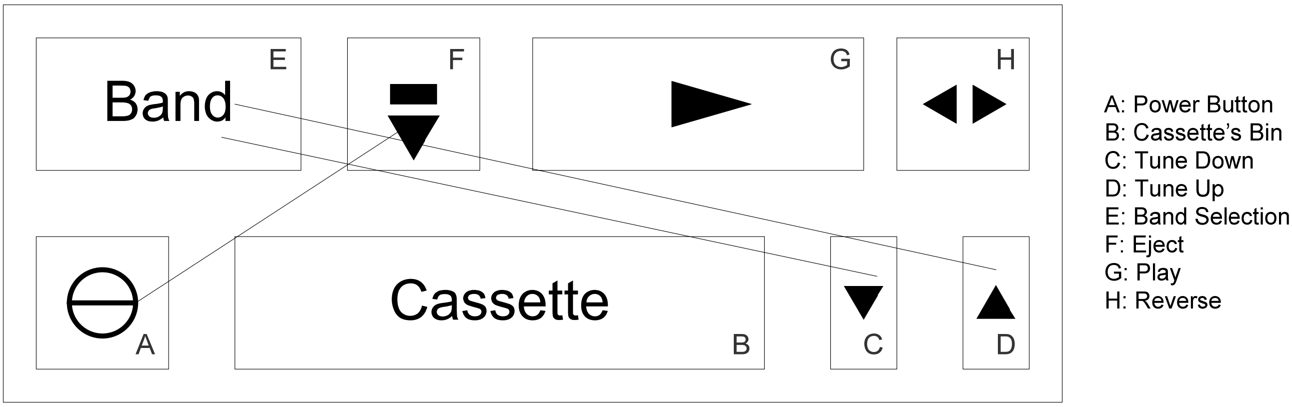


Figure 1. Link diagram of an in-car audio

Table 1. Link Table of an in-car audio (unused area)

	A	B	C	D	E	F	G	H
A						1		
B								
C					1			
D					1			
E								
F								
G								
H								

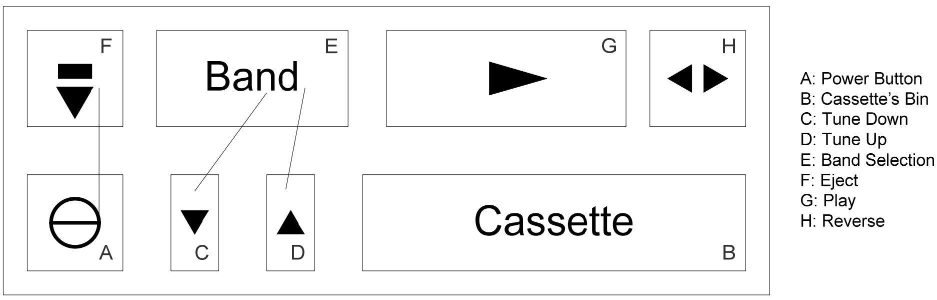


Figure 2. Improved in-car audio interface by traditional link analysis

It is obvious that the traditional link analysis method has two potential limitations. First, in reality, as long as there is certain physical distance between a user and a user interface, operating an interface consists of two types of movements— movements between the user and the interface (U-I movements) and within interface movements (W-I movements) (See Figure 3). In the previous in-car radio example, a driver may move their hand toward the radio control panel first and then press a sequence of buttons to achieve a desired function, such as searching his or her favorite station. The movement of his or her hand toward the panel is a U-I movement while the movements betweens functional buttons on the panel are W-I movements. The link table referred by traditional link analysis method only considers the W-I movement while the U-I movement is not considered. The U-I movement represents the back-and-forth motion of the operator's hand between the origin (the hand position in resting posture) and the target element, while the W-I movement represents the motion from one element to another. The link table only contains information of W-I movements by tabulating all links between elements on the target interface so that the designer can minimize the distance between linked elements; however, as long as there is certain physical distance between a user and a user interface, the user must perform U-I movements to access the user interface. Hence, the easiness of performing U-I movements (called "Accessibility" in this paper), should be considered.

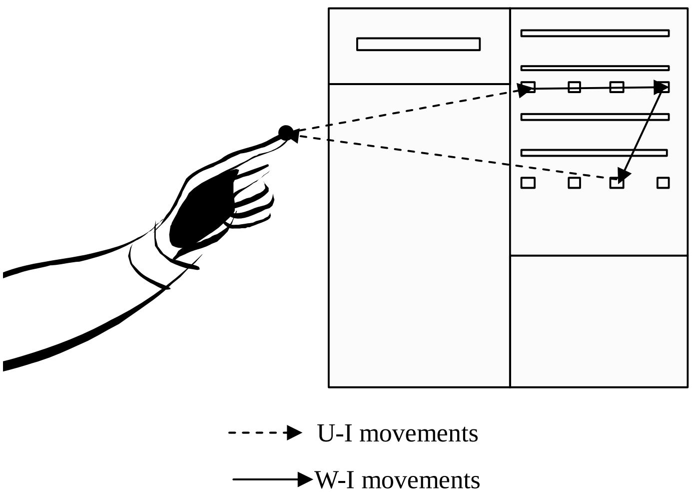


Figure 3. Movements between the user and the interface (U-I) and within interface (W-I)

Second, every physical movement of the hand has its direction (back and forth), but the link table of the traditional LA regards the forward and the backward movement as the same. Directional information is important especially when the designer takes the difficulty index into consideration. Difficulty is determinant of time performance and the difficulty index, such as $\log_2(2A/W)$ proposed by Fitts (Fitts 1954) and other modified index for either bivariate or 3 dimensional pointing task, can be a function of distance, effective target width and directional angle. Neither target nor directional angle can be determined without information of moving direction (MacKenzie 1989, Murata and Iwase 2001, Johnny and Shumin 2003, Du *et al.* 2007). Hence, 2 types of movements and their directions should be incorporated into the link table so that the overall cost of operating an interface would not be biased or underestimated during the process of optimization.

In addition, the concept of the “link” also cannot properly reflect the cost of operating the target interface in terms of construct validity. Ideally, it is better to consider the link value as a composite frequency-importance index (Sanders and McCormick 1993). However, based on the ordinary definition of the link value, it only counts the number of movements between elements, and equal weights are assigned to each link. In fact, links should be quantified by either physical or temporal distance between 2 connected elements, and each link should have different weight according to its importance and frequency. The importance should be a function of seriousness of erroneous use and the frequency should consider how often an operation would be performed in a long term rather than in a single run of all functions. Obviously, counting number of links is not a valid way to well consider transitional cost of links and their relative weights.

Link analysis method is supposed to be consistent if it is conducted by different professionals, but the procedure of conducting varied significantly. Previous link-related studies suggested different link analysis methods when target interfaces had different features and when the operator performed different tasks (Rabideau and Farnady 1976, Pulat and Ayoub 1985, Sears 1993, SARGENT *et al.* 1997, Yin and Lee 2004). The variability in methodological approaches has been regarded as one important factor causing inconsistency in usability evaluation. Even with the same basic methodology, the outcome of usability evaluation could be very different due to differences in choosing tasks and content settings to be evaluated (Molich *et al.* 2004). The situation in which the operator needs to perform procedural operations was quite different from that the user could arbitrarily perform certain steps to complete the final goal. The variability associated with the types of the user interfaces and the nature of the tasks implies that for link analysis, applicable interfaces should be defined by demand properties (physical/cognitive), representation features (fixed/dynamic) and expected user behaviors (procedural/random). If the demand properties, the representation features and the expected user behaviors of the target interface are not well defined, the cost may not be valid to evaluate the usability of the target interface.

Several works used a computer program to automatically allocate controls and displays in a user interface (Regarded as Automatic Generation of User Interface (AGUI) (Rabideau and Farnady 1976, Pedro 1990, Won Chul and James 1990, Dennis *et al.* 1992)), or applied computational models to help user interface designers to allocate the elements (Wu and Liu 2007d, Wu *et al.* 2008, Wu and Liu In Press). However, most of these studies were conducted by experts of computer science, and they focused on how to match programming specifications to a given widget library to generate a layout based on the designer's point-of-view, maximizing the utility of space; however, the two limitations of traditional LA have not been addressed systematically in these studies.

The objective of this study is to propose an improved link analysis method which includes a modified link table that could account for both types of movements and contained directional information of movements. First, an extra element, the hand origin, would be included in the modified link table so that the U-I movements could be represented in cells associated with the hand origin. Second, rows and columns were used separately to indicate the initiation and the end of the movements and, in turn, the direction of movements could be determined by their positions in the modified link table. That is, each link value in a cell represents the relative weight of the movement, either a U-I or a

W-I movement, and its direction can be seen by the location of the cell into which it is filled. In addition, the link value was redesigned to incorporate the frequency and the importance into one composite index so that this index could be appropriate weight for transitions. The difficulty index of transition, which is determinant of performance time, was then considered the representative of transitional cost and weighted by the link values. Hence, the weighted index difficulty can be more representative of overall transitional cost. Finally, the overall transitional cost would be optimized through the branch-and-bound algorithm. A case study in a real-world nuclear control system was proposed to illustrate how to use the new method in practice. Based on the case study, an experiment was conducted to validate effectiveness of the new method in comparison with the traditional LA method in terms of reducing users' performance time.

2. Development of the Improved Link Analysis Method

To optimize an interface layout and quantitatively evaluate its usability, the cost of operating the interface in terms of temporal, physical or cognitive expense should be formulated first. The overall transitional cost that represents the extent of physical demand during U-I and W-I movements were used in the algorithm as the cost to be minimized. It is assumed that the cost of each movement (transition) would be a function of its difficulty, and the difficulty of each transition should be weighted by its importance and frequency. Based on the assumption of procedural operations, the operational cost of each transition should be additive and the overall cost should be the summation of the weighted difficulty index of all existed transitions, including U-I and W-I movements. Then a simple branch-and-bound algorithm with some modifications, including the priority of entering searching tree, the principle of searching optimal layout and the cut-off strategy for branching, would be adopted to generate the optimal interface layout. The formulation of objective function (minimizing overall transitional cost) and the optimization-based layout generation algorithm would be explained in the following.

2.1 Overall Transitional Cost

The goal of link analysis is to minimize the overall transitional cost while the user operates an interface. This notion can be stated as the following expression:

$$\text{Overall Transitional Cost} = \sum_{\text{All Transitions}} (\text{Weight of Transition} \times \text{Cost of Transition}) \quad \text{..........................} (1)$$

The weight of each transition can be considered a composite index of importance and frequency, and the cost of each transitional relates to its demanding efforts. In this study, we assumed that the demanding effort of each transition (movement) is positively proportional to its difficulty level, and the difficulty index should be a function of effective target width, moving distance and moving direction (if it is 3-D movement.) Transitional cost is closely related to usability evaluation. The ISO standard defines usability as "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction". The "effectiveness" includes accuracy, and the "efficiency" is the resources expended in relation to the accuracy (Hornbæk 2006). The cost of transition considers both effective target width and moving distance and they are associated with accuracy and energy expenditure, respectively. Therefore, the transitional cost can account for effectiveness and efficiency of usability in physical aspect. Besides, "satisfaction" is defined as "freedom from discomfort, and positive attitudes towards the user of the product". Apparently, transitional cost represents the physical demand and minimization of overall transitional cost can reduce the risk of having physical discomfort and its resultant negative user experiences. In fact, physical and physiological index are commonly used in the evaluation of usability (Lin *et al.* 2007). Finally, time-based performance is widely used in studies of usability evaluation (Sears 1993, Grobelny *et al.* 2005, Dan *et al.* 2008). Since difficulty of transitions determines movement time and physical demand to a large extent, it should be reasonable to use total transitional cost as an important index of usability.

2.2 Modified Link Table

To improve traditional link analysis method, there are two problems to be addressed—the negligence of U-I movements and the difficulty of movements. The information about the origin of each operation and the direction of each movement should be incorporated in the modified link table. Traditional link table listed only elements to be considered on the interface and only half of the table was used (See Table 2).

Table 2. Traditional link table (unused area)

	E_1	**E_2**	**…..**					**E_n**
E_1		L_{11}						L_{1n}
E_2								L_{2n}
.								
.								
.								
.								
.								
E_n								

In this study, the origin of the operation was considered an extra element in the link table, and the flip side of the link table was utilized. The modified link table is shown in Table 3. All start points are defined in rows and all targets are defined in columns, respectively. The 1st column and the 1st row represent all U-I movements because O stands for the origin of the hand. In consequence, the link values L_{0i} represents the frequency-importance composite weight of movement from origin to element i. Similarly, the link values L_{i0} represents the weight of movement from element i to origin. L_{ij} for any $i \neq j \neq 0$ stands for the weight of movement from element i to element j. In this modified table, the identification of U-I movements and directions of all movements is possible. This would facilitate computation of difficulty indices based on different types and directions of movements.

Table 3. Modified link table

Targets

Start Points

	O	**E_1**	**E_2**	…..					**E_n**
O		L_{01}	L_{02}						L_{0k}
E_1	L_{10}		L_{11}						L_{1n}
E_2	L_{20}	L_{21}							L_{2n}
.									
.									
.									
.									
.									
E_n	L_{n0}	L_{n1}	L_{n2}						

2.3 Composite Importance-Frequency Weight

The link values in the link table, ideally, should be a composite importance-frequency weight of each transition. However, traditional link analysis did not well define the frequency and the importance in the context of tasks. The relative importance and holistic using frequency should not be determined in the operational level because the link, which is the movement between two elements on the interface, is defined in the functional level. Without predetermined functions and specified sequences, links cannot be defined in that the user cannot just arbitrarily use certain buttons in a particular sequence without knowing what this procedure is going to do. Since the frequency and the importance were the intrinsic features of a link instead of an element (the goal is to determine the frequency and the importance of links, not of elements), the frequency and the importance should be decided in the functional level.

For frequency, the total usage of a function over a specified period of time can be obtained by an observation or a survey. When it is not possible to conduct such an observation, survey or the target interface to be modified does not even exist yet, a heuristic procedure can be adopted. A group of designers and usability experts can give each function a frequency based on expected long-term usage. Then the relative frequency index of function k can be computed as the following:

$$F_k = \frac{f_k}{\sum_{k=1}^{m} f_k} \text{(Frequency Index of Function k)} ;\ 0< F_k <1;\ \sum_{k=1}^{m} F_k = 1 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where m is the total number of functions, and f_k is the relative frequency of usage for function k.

For importance, a pair-wised comparison can be conducted to decide the relative importance of each function. (Hart and Staveland 1988) The relative importance can be decided by considering the following 2 principles:

1. Criticality: which one is more related to safety issue and more likely to cause serious damage if being erroneously used?
2. Substitution: which one can be possibly replaced by combining other basic functions?

Then the relatively important function can be given a value 1, and a value 0 is given to the other.

The importance index of function k can be calculated as the following:

$$I_k = \frac{\sum_{v=1}^{C_m^2} i_v}{C_m^2} \text{(Importance Index of Function k)} ;\ I_v = (0, 1);\ \sum_{k=1}^{m} I_k = 1 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where i_v is the importance value for function k obtained from each pair-wise comparisons, either 1 or 0.

And for any transition from element i to element j, the link value L_{ij} should be:

$$L_{ij} = \sum_{k=1}^{m} I_k \cdot F_k \cdot C_{ijk} \text{(Link value form } E_i \text{ to } E_j \text{; for all } i \neq j) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where C_{ijk} is the number of movements from element i to element j in function k. This value could be used as relative weight of each transition.

2.4 Difficulty Index of U-I and W-I movements

Mackenzie (1989) suggested the following modified difficulty index for 2 dimensional movements:(MacKenzie 1989)

$$DI_{2D} = \log_2(d/s+1.0) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where d and s are the distance from the starting point to the target and the size (diameter) of the target, respectively. Murata (2001) extended this index to account for 3 dimensional movements: (Murata and Iwase 2001)

$$DI_{3D}=log_2(d/s+1.0)+0.5\sin\theta \quad (6)$$

where θ is the directional angle relative to the target. In this study, DI_{3D} and DI_{2D} are used as the difficulty index of U-I and W-I movements, respectively. For movements from interface back to hand origin, the target size is regarded as infinity and the DI_{3D} becomes $0.5\sin\theta$.

2.5 Objective Function of Optimization

Consider a target interface with n elements to be arranged in a rectangular space. This area is assumed to have $P \times Q$ basic units with identical area in width and height dimension. The interface has m functions. After we arrange all elements into the space, the total transitional cost of an element s at location $U_{x,y}$ can be computed as:

$$T_s= L_{0s} \cdot DI_{3D}(O,E_s) + L_{s0} \cdot DI_{3D}(E_s,O) + \sum_{i=1}^{n} L_{si} \cdot DI_{2D}(E_s,E_i) + \sum_{j=1}^{n} L_{js} \cdot DI_{2D}(E_j,E_s) \quad (7)$$

where $DI_{2D/3D}(E_1,E_2)$ signifies the 2D/3D difficulty index of transition from E_1 to E_2. L_{0s}, L_{s0}, L_{si} and L_{is} can be found in the link table at the corresponding cells, and DI can be computed based on Equation (5) and (6). Therefore, the objective function to optimize the overall transitional cost of using this interface would be:

$$\text{Minimize } \sum_{s=1}^{n} T_s \quad (8)$$

2.6 Layout Generation Algorithm

The solution of optimization problem can be difficult and complicate if mathematical or computational method is utilized (Wu and Liu 2004c, Wu and Liu 2008a, Wu *et al.* 2008d). One of the heuristic ways to solve this optimization problem is using branch-and-bound algorithm. The initial application of branch-and-bound algorithm in user interface can be found in Sears's work (Sears 1993). In this study, the branch-and-bound algorithm was adopted and modified to provide a practical and feasible heuristic algorithm. First, instead of using frequency as the only priority index to decide the sequence of entering searching tree, 2 new indices, Accessibility Priority Index (AI) and Proximity Priority Index (PI), were used to identify the element with potentially higher cost if it was placed in the wrong position so that the better layout could be considered first. Second, the searching principle for allocating the element to be arranged would depend on relative quantity of AI and PI, so that possible layout alternatives could be eliminated. Thirdly, only two alternative layouts, the optimal and the sub-optimal one, would be kept in the searching tree so that the bad layouts could be excluded faster.

2.6.1 Priority of Arrangement

Consider that only the distance between elements and the directional angle are indecisive before the final layout is done. That is, if we decompose T_s into four components:

$$T_s = L_{0s} \cdot DI_{3D}(O, E_s) + L_{s0} \cdot DI_{3D}(E_s, O) + \sum_{i=1}^{n} L_{si} \cdot DI_{2D}(E_s, E_i) + \sum_{j=1}^{n} L_{is} \cdot DI_{2D}(E_j, E_s) \quad (9)$$

$$L_{0s} \cdot DI_{3D}(O, E_s) = L_{0s} \cdot [\log_2(d_{Os} / \mathrm{s_s} + 1.0) + 0.5\sin\theta] = W_{os} \times f(d, \theta) \quad (10)$$

$$L_{s0} \cdot DI_{3D}(E_s, O) = L_{0s} \cdot [0.5\sin\theta] = W_{so} \times f(\theta) \quad (11)$$

$$L_{si} \cdot DI_{2D}(E_s, E_i) = L_{si} \cdot \log_2(\mathrm{d_{si}/s_i} + 1.0) = \mathrm{W_{si}} \times f(d_{si}) \quad (12)$$

$$L_{is} \cdot DI_{2D}(E_i, E_s) = L_{is} \cdot \log_2(\mathrm{d_{is}/s_s} + 1.0) = \mathrm{W_{is}} \times f(d_{is}) \quad (13)$$

The value of W_{os}, W_{so}, W_{si} and W_{is} are predetermined constants before the elements are arranged and would not change with layouts. Therefore, the weights of different types of links can be determined as the following:

$$W_{os} = L_{0s} \cdot [\log_2(1/\mathrm{s_s} + 1.0)] \quad (14)$$

$$W_{so} = L_{s0} .0 = 0 \quad (15)$$

$$W_{si} = L_{si} \cdot [\log_2(1/\mathrm{s_i} + 1.0)] \quad (16)$$

$$W_{is} = L_{is} \cdot [\log_2(1/\mathrm{s_s} + 1.0)] \quad (17)$$

Since Equation (14) and (15) relates to U-I movements, W_{os} and W_{so} can be considered accessibility priority index:

$$AI_s = W_{os} \quad (18)$$

Similarly, Equation (16) and (17) relates to W-I movements, W_{os} and W_{so} can be regarded as proximity priority index:

$PI_{is} = W_{si} + W_{is}$ .... (19)

The priority index is then determined by

$(AI_s + \sum_{\text{All arranged items}} PI_{is})$ .... (20)

In the first phase, only the hand origin (O) is available, and so the element with highest AI will be considered first. After the first element is placed, the following element to be arranged will be decided based on Equation (20).

2.6.2 Searching Principle for Optimal Positions of Elements

A concentric searching strategy was adopted in this study (Pulat and Ayoub 1985). Basically, the searching center would be determined first by considering Equation (20). For an element to be arranged (Es), if $AI_s > \sum_{\text{All arranged items}} PI_{is}$, then the searching center should be the hand origin. And if $AI_s < \sum_{\text{All arranged items}} PI_{is}$, the searching center should be the element i. The algorithm considered the position closest to the center first and then shift concentrically until the $\sum_{\text{All arranged items}} T_s$ could not be further improved. In case $AI_s = \sum_{\text{All arranged items}} PI_{is}$, the algorithm would consider the hand origin as the center because the accessibility consider directional effects and therefore was more constrained than the proximity.

2.6.3 Branch-and-bound

After the priorities of the elements were determined, the sequence of elements entering the searching tree would be decided accordingly. Then based on the searching principle, the algorithm would find the optimal layout and the sub-optimal layout for the current element to be arranged. The layout then would be branched from these two layouts and from all branches of the searching tree, find the next two layouts to be kept. The heuristic optimization-based algorithm was summarized in Table 4.

Table 4. Branch-and-bound algorithm

1. User inputs the weighted link table.
2. Compute Accessibility Priority Index of each element defined in the link table by Equation (18).
3. Compute Proximity Priority Index of each link defined in the link table by Equation (19)
4. Tabulate all AI_s and PI_s.
5. Determine the sequence of elements entering the searching tree by Equation (20).
6. Assign the current element to be arranged (Es) according to the sequence in step 5.
7. Search optimal and sub-optimal layout for Es based on the searching principle. (Min $\sum_{\text{All arranged items}} T_s$)
8. Check if there is any geometric constraint to be enforced.
9. Check if all elements are arranged (A_s=1 for all A_s, s=1 to n). If all elements are arranged, then terminate the layout generation. Otherwise, continue finding the next candidate element to be arranged.
10. Find the next element to be arranged with the highest priority = ($AI_s + \sum_{\text{All arranged items}} PI_{is}$)

3. A Case Study and Experimental Validation of the Improved LA Method

3.1 Background

For demonstration and validation purposes, a simplified control interface of a boiling water reactor in a real-world nuclear control system and operation was utilized to elucidate the algorithm and layout generation in detail (Dix *et al.* 2003, Anon 2008). The simplified design of the boiling water is shown in Figure 4. The interface contained 9 elements to be arranged. Each one of them was either only 1 button or a functional group of several buttons. The functions of the interface and their relative frequency of usage are listed in Table 5.

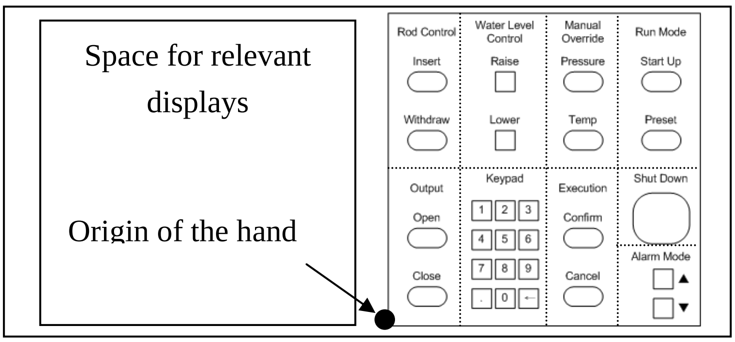


Figure 4. The simplified design of the boiling water reactor (BWR) interface (Dix *et al.* 2003)

Table 5. The functions of the boiling water reactor (BWR) interface (Dix *et al.* 2003)

Functions and Operations	Relative Frequency of Usage (per 100 times)
1. Start Up: Warm up reactor to minimal power Operations: O→Start Up→O	1
2. Preset: Operate reactor under presetting condition Operations: O→Preset→Keypad(# of presetting condition)→Confirm→O	10
3. Shutdown: Shutdown reactor Operations: O→Shut Down→Confirm→O	1
4. Alarm Mode: Adjust sensitivity of alarm Operations: O→▲/▼→O	15
5. Manual Override: Manually set pressure/temperature Operations: O→Pressure/Temp→Keypad (# pressure/temp in psi or degree)→Confirm →O	10
6. Water Level Control: Riase/lower water level inside the reactor Operations: O→Raise/Lower→O	35
7. Rod Position control: Adjust rod position to control reaction speed Operations: O→Insert/Withdraw→Keypad (# of reaction rod)→Confirm→O	20
8. Output Control: Couple/decouple generator to output circuit Operations: O→Open/Close→Confirm→O	4
9. Cancel Operations: Terminate all indecisive operations Operations: O→Cancel→O	4

The size of the BWR interface was assumed to be 40 cm high and 40 cm wide, and it was supposed to be placed at the right side of a big control panel because the left side of the panel is the space for relevant displays. Consequently, the origin of the hand should be close to the lower-left corner of the interface, and the distance from the origin of the hand to the interface was assumed to be 15 cm. Based on the configuration, the interface could be therefore regarded as a space containing 4X4 units of 10X10cm area. Then number 1 through 9 was assigned to each element as index number for further analysis. The mapping of elements to the interface was shown in Figure 5.

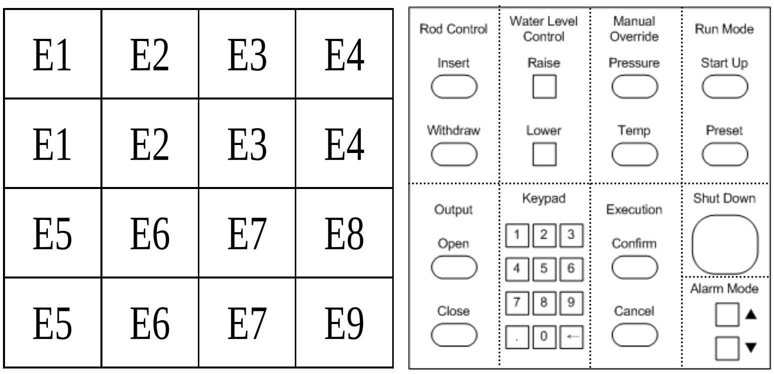


Figure 5. The mapping of conceptual elements to the real interface

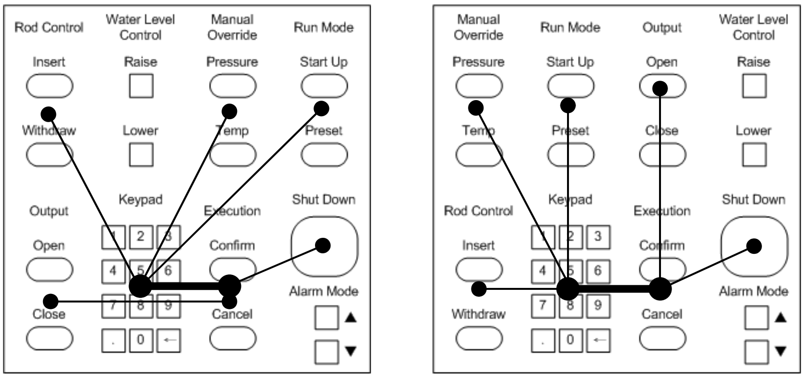
Before the analysis, some assumption should be established to facilitate the calculation of transitional cost. First, the parameter d in the difficulty index was calculated based on the distance from the centroid of one element to another. Second, the parameter s in the difficulty index was determined based on the button size. There were 3 different button sizes— 1.5, 5 and 6 cm for small, medium and large buttons, respectively, and the parameter s was determined by the button size contained in the target elements accordingly. For example, to calculate the transitional cost from E5 to E6, the distance parameter d was calculated form the centroid of E5 to the centroid of E6, and the effective target width parameter was 1.5 (the button size of keypad).

3.2 Traditional link analysis method

Based on Table 1, the traditional link table could be constructed in Table 6. This unweighted table could only show how many links between elements in one run of 9 functions and did not contain any information about moving directions. However, it was sufficient to traditional link analysis method and the original interface can be improved in terms of the proximity between elements. Figure 6 compared the original interface with the modified interface through traditional link analysis.

Table 6. Traditional link table (unused area)

	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1		0	0	0	0	1	0	0	0
E2			0	0	0	0	0	0	0
E3				0	0	1	0	0	0
E4					0	1	0	0	0
E5						0	1	0	0
E6							3	0	0
E7								1	0
E8									0
E9									



*The thickness represents the strength of link

Figure 6. Comparison of the original (left) and the modified (right) interface through traditional link analysis

The improvement through traditional link analysis was obvious that the distance of link E1-E6, E1-E4, and E5-E7 was shortened. From a usability point of view, the overall movements required for operating the interface would be reduced effectively so that excessive physical demand and possible upper extremities discomfort could be ameliorated in a long term. However, the position of E3 (Manual Override), E4 (Run Mode) and E1 (Rod Control) was interchangeable. Even if the interface was vertically or horizontally flipped, the assessment would be the same based on traditional link analysis as long as the relative distance and location among control elements remained the same. Figure 7 showed the flipped interfaces and the vertically flipped interface would be more difficult to operate if the operation originated from the lower-left corner. In fact, the operation would not always originate from the center of the interface, especially for those relatively large interfaces. For those interfaces of which the origin of the hand was not at the center, the relative distance and location of control elements to the origin should be taken into consideration in addition to the relative distance and location among control elements.

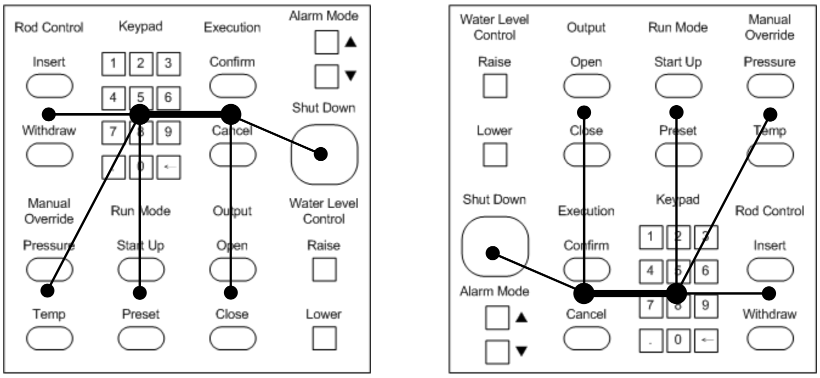


Figure 7. Flipped Interface (Left: Vertically flipped Right: Horizontally Flipped)

3.3 Improved link analysis method—modified link table and optimization-based algorithm

According to improved link analysis method suggested in this study, a modified link table could be constructed in Table 7. Notify that the rows represented all starting elements and the columns stood for all target elements for operations. O signified the extra element of the hand origin and shaded area, which were cells in the 1st column and the 1st row, showed the weighted strength of link between each element and the hand origin. The link values were calculated based on Equation (4). The importance of all elements was not manipulated in that the importance could not easily be reflected by completion time and the succeeding validation considered completion time the only dependant variable. Then, based on the information provided by Table 5 combined with the physical dimension of the interface, the accessibility and proximity priority index could be calculated separately by Equation (18) and (19). Those indices were tabulated in Table 8.

Table 7. Modified link table

	O	E1	E2	E3	E4	E5	E6	E7	E8	E9
O		0.2	0.35	0.1	0.11	0.04	0	0.04	0.01	0.15
E1	0		0	0	0	0	0.2	0	0	0
E2	0.35	0		0	0	0	0	0	0	0
E3	0	0	0		0	0	0.1	0	0	0
E4	0.01	0	0	0		0	0.1	0	0	0
E5	0	0	0	0	0		0	0.04	0	0
E6	0	0	0	0	0	0		0.4	0	0
E7	0.49	0	0	0	0	0	0		0	0
E8	0	0	0	0	0	0	0	0.01		0
E9	0.15	0	0	0	0	0	0	0	0	

Table 8. Accessibility and Proximity Indices

Accessibility Priority Index (AI)	Proximity Priority Index (PI)
AI_1= 0.05	PI_{16}= 0.15
AI_2= 0.26	PI_{36}= 0.07
AI_3= 0.03	PI_{46}= 0.07
AI_4= 0.03	PI_{57}= 0.01
AI_5= 0.01	PI_{67}= 0.11
AI_6= 0.00	PI_{87}= 0.00
AI_7= 0.01	(All other PI=0)
AI_8= 0.00	
AI_9= 0.04	

Based on Table 8, the sequence of the elements considered in the searching tree could be determined by AI and PI associated with arranged elements in different phase. For example, in the first phase the hand origin (O) was the only elements arranged, so E2 (AI=0.26) would have the highest priority and entered the searching tree first. After E2 was arranged, E1 should be the next element to be considered because E2 did not link with any elements and E1 had the highest AI (0.05) except for E2. Then after E1 was arranged, E6 should be the next one because:

$$\text{Priority of Es} = (AI_s + \sum_{\text{All arranged items}} PI_{is}) \quad (20)$$

$$\text{Priority of E3} = (AI_3+PI_{23}+PI_{13}) = AI_3+0+0 = 0.03 \quad (21)$$

$$\text{Priority of E4} = (AI_4+PI_{24}+PI_{14}) = AI_4+0+0 = 0.03 \quad (22)$$

$$\text{Priority of E5} = (AI_5+PI_{25}+PI_{15}) = AI_5+0+0 = 0.01 \quad (23)$$

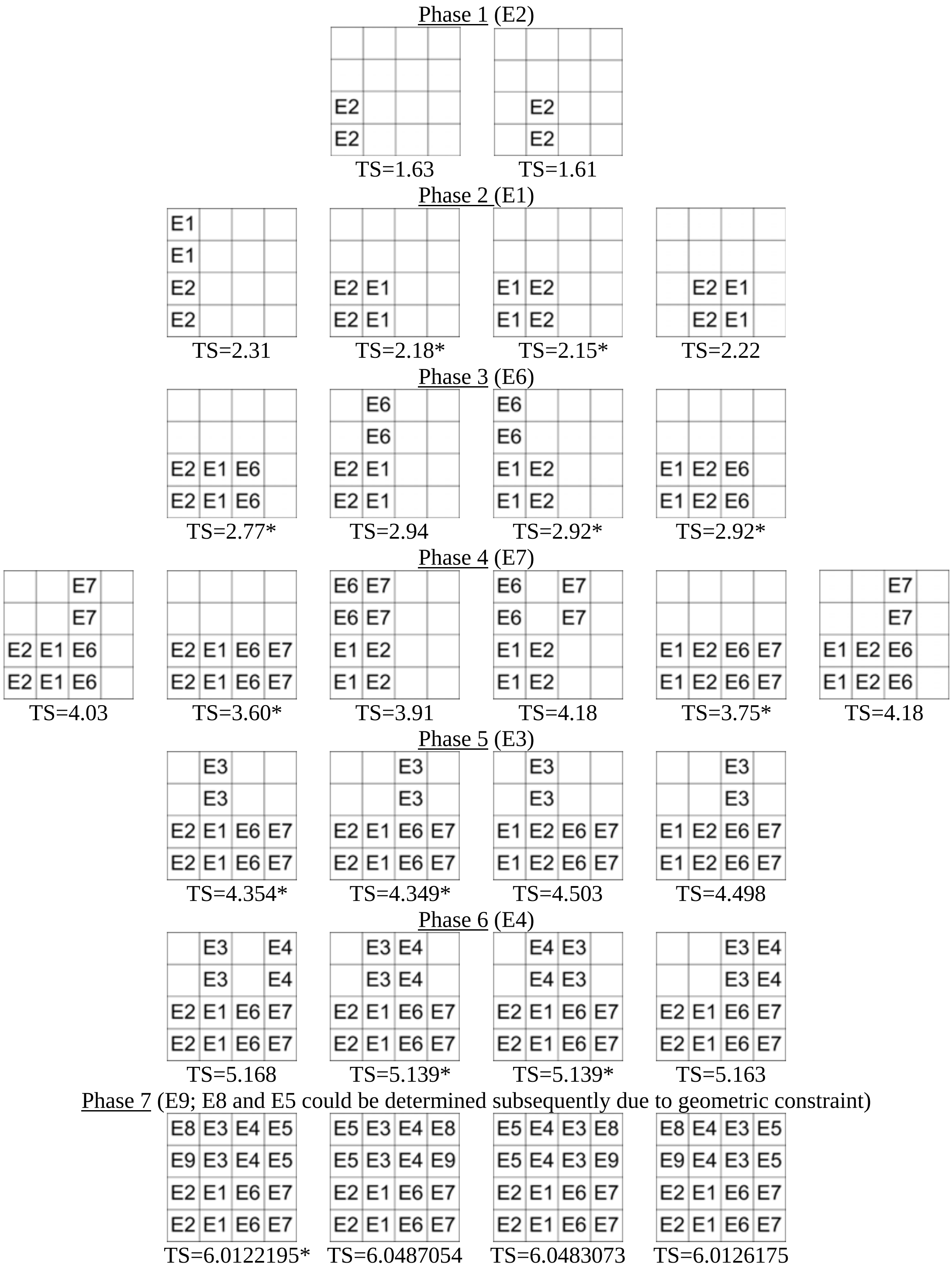
$$\text{Priority of E6} = (AI_6+PI_{26}+PI_{16}) = 0+0+ PI_{16}= 0.15 \quad (24)$$

$$\text{Priority of E7} = (AI_7+PI_{27}+PI_{17}) = AI_7+0+0 = 0.01 \quad (25)$$

$$\text{Priority of E8} = (AI_8+PI_{28}+PI_{18}) = AI_8+0+0 = 0.00 \quad (26)$$

$$\text{Priority of E9} = (AI_9+PI_{29}+PI_{19}) = AI_9+0+0 = 0.04 \quad (27)$$

And then E7 had the highest priority after E6 was arranged (Priority of E7 = $AI_7 + PI_{67} = 0.12$). Through a similar way E3, E4, E9, E8 and E5 were arranged in sequence. Figure 8 showed the whole searching tree that in each phase only the optimal and the sub-optimal layout were kept for further branching. By applying geometric constraint (E9, E8 and E5) the searching can be done with in 7 phases and in each phase there were usually only 4 layouts to be compared. (There were 6 layouts to be compared in phase 4 because 2 layouts had the same TS value in addition to the optimal one in phase 3.) The selection of candidate layouts in each phase followed the searching principle in the algorithm so that alternative positions for the element to be arranged would be fewer than all possibilities. In this case, none of the element had to try more than 5 positions. Therefore the optimal layout can be obtained within 50 calculations. The optimal layout was shown in Figure 9. It was worth notifying that in comparison with modified interface by traditional link analysis method, the linking structure of E1, E3, E4, E5, E6 and E7 was kept, while the link between E7 and E8 was sacrificed to trade off available space closed to the hand origin for E2 and E9, which demanded more accessibility. Although the linking structure was moved to the right side and its transitional cost would increase to some extent, the overall cost of the optimal interface would be still better than traditionally modified one (6.01 vs. 6.26) based on quantitative assessment. The numeric difference between these 2 interfaces seemed relatively small, but it could cause significant difference under intensive and repetitive operating every day.



* Interfaces that were kept for further branching

Figure 8. The branch-and-bound searching tree

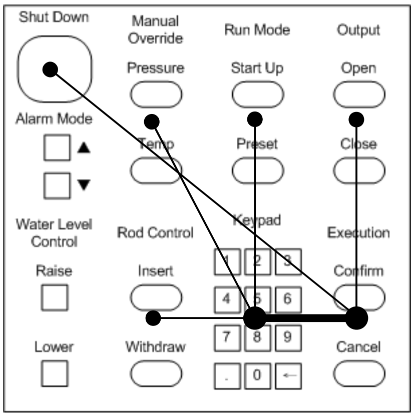


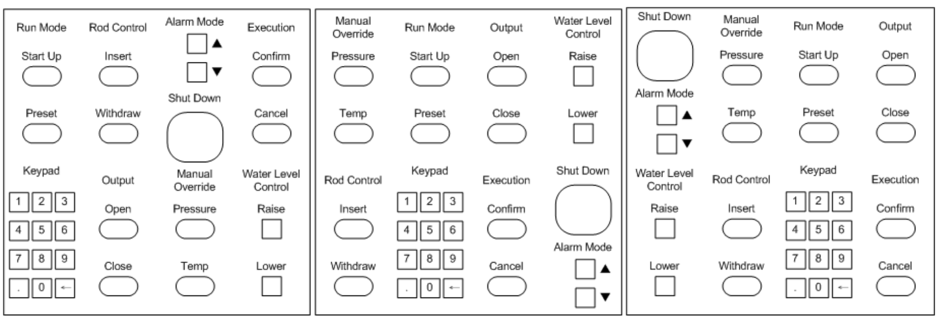
Figure 9. The optimal interface layout

3.4 Experimental Validation

To validate the quantitative assessment and the improvement of the new method, an experiment was conducted to compare the temporal difference of operating 3 interfaces.

3.4.1 The layouts

The layout of RAN (RAN stands for "randomized") interface was generated randomly and used as a baseline measurement of operating time. The TLA (TLA stands "modified by traditional link analysis") and OPT (OPT means "modified by improved link analysis method" suggested in the study) interfaces were modified by traditional and improved link analysis method, respectively (see Figure 10). The different design of layouts would be regarded as independent variables in the experiment and the completion time of performing a simulative task on these three interfaces would be measured as the dependent variable and analyzed statistically.



RAN (TS=6.94) TLA (TS=6.26) OPT (TS=6.01)

Figure 10. 3 interfaces to be compared and their TS value

3.4.2 Subjects and Experimental Task

6 subjects (3 male, 3 female, all college students aged 20~30 and right-handed) were recruited to perform a simulated task consisted of 20 operations (see Table 9) (Similar validation studies also used this similar amount of subjects, see Wu & Liu, In Press). The 20 operations were composed of mixture of 9 real-world functions in Table 5 and the repetitions of each function were designed to be comparable with relative frequencies in Table 5. The subject was required to perform 2 trials of experimental task on 3 interfaces, and the variability of completion time between 2 trials on the same interface should not exceed 5%. Otherwise, the subject needed to perform another trial until the criterion of variability was satisfied. During the experiment, both the run order of operations and the sequence of interfaces were randomized to eliminate any learning effects and time effects. In addition, a practice trial was given to the subject before the experiment and extra time of practice was available if the subject or the experimenter felt necessary.

Table 9. Experimental Task*

Number	Function	Operation
1	Preset	O→Preset→Keypad(1)→Confirm→O
2	Output Control	O→Close→Confirm→O
3	Water Level Control	O→Raise→O
4	Water Level Control	O→Raise→O
5	Water Level Control	O→Raise→O
6	Alarm Mode	O→▼→O
7	Rod Position control	O→Withdraw→Keypad(2)→Keypad(3)→Confirm→O
8	Manual Override	O→Pressure→Keypad(3)→Keypad(0)→Keypad(0)→Confirm→O
9	Preset	O→Preset→Keypad(8)→Confirm→O
10	Alarm Mode	O→▲→O
11	Alarm Mode	O→▲→O
12	Rod Position control	O→Insert→Keypad(1)→Keypad(5)→Confirm→O
13	Water Level Control	O→Lower→O
14	Water Level Control	O→Lower→O
15	Water Level Control	O→Lower→O
16	Cancel Operations	O→Cancel→O
17	Manual Override	O→Temp→Keypad(1)→Keypad(2)→Keypad(5)→Keypad(0)→Confirm→O
18	Rod Position control:	O→Insert→Keypad(2)→Keypad(3)→Confirm→O
19	Rod Position control	O→Withdraw→Keypad(1)→Keypad(5)→Confirm→O
20	Water Level Control	O→Raise→O

*the repetition of the operations tends to simulate the relative frequency indicated in Table □.

3.4.3 Experimental Setup

The environmental setting of the experiment was shown in Figure 11. A testing panel was placed on the desk and the interface to be tested was attached to the right side of it. A switch was placed on the surface of the desk at a distance of 15 cm in front of the panel to control the hand origin and linked to a timer. Another indicator was placed on the top of the panel and linked to the probe attached to the subjects' right index finger so that whenever the subject correctly touched the button, it would light on. The subject was instructed to adjust posture to his/her preference and the distance of the panel was adjusted accordingly so that the subject could reach the farthest button without any difficulty and place the tip of their right index finger on the switch as the elbow can rest on the desk surface.

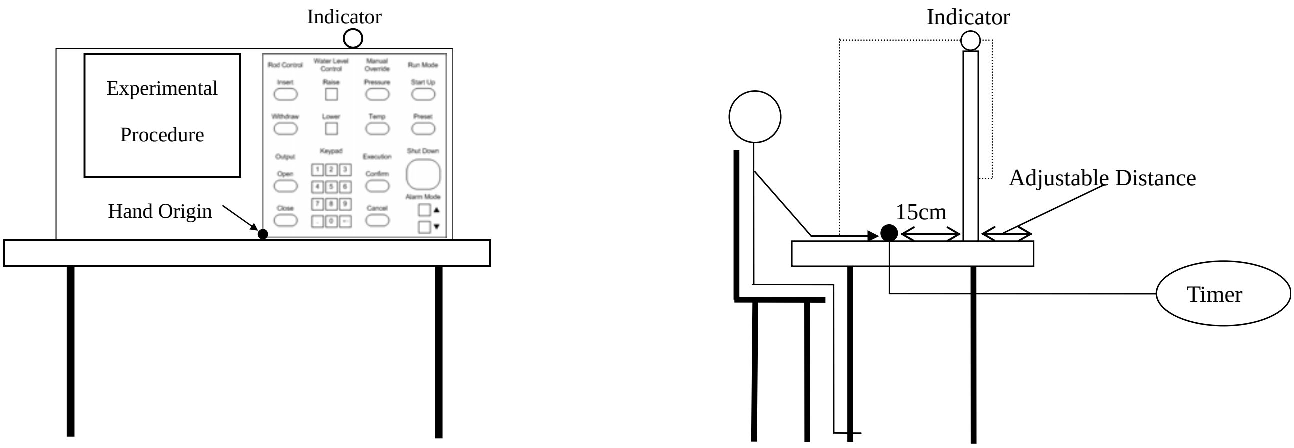


Figure 11. Environmental settings of experiment (Left: front view; Right: side view)

3.4.4 Experiment Procedure

Before performing the experimental trial, subjects were asked to perform each step in the operation in a smooth trajectory without jerking motions. To eliminate the effect of cognitive effort and visual search, subjects were also allowed to familiarize the sequence of steps in advance and then, smoothly perform the task as quick as possible. When subjects were asked to perform the task, firstly the experimenter would give him/her the number of the operation to be performed in the task. Then s/he would check the experimental procedure sheet attached on the left side of the panel to find out the operation and push the buttons step-by-step. Each operation began and ended with a click of the switch, and contained 1 to 6 buttons to be pushed in between. The total completion time of one task would be recorded in the computer. If during the task one button was not touched correctly (the indicator would not light on), an error associated with the operation would be recorded and the subject would be asked to do the operation again. After trials were done, variability in terms of total completion time within 2 trials would be calculated to determine if another trial was necessary. After 2 or more trials were done in one interface and the variability fulfilled 5% criterion, 10 minutes break would be given to the subject. Then the procedure would be repeated on another interface until all 3 interfaces were tested

3.4.5 Experimental Results

The results of interface testing were shown in Table 10. The total completion time (CT) were separated into two components: the completion time of operations that were only associated with accessibility (AT, contained time of operation 3, 4, 5, 6, 10, 11, 13, 14, 15, 16 and 20) and the completion time of proximity-associated task (PT, contained time of operation 1, 2, 7, 8, 9, 12, 17, 18 and 19). In average, subjects completed experimental task significantly faster on the OPT interface than on the TLA interface and RAN interface. Figure 12 compared the total completion time on 3 interfaces. The difference between 3 interfaces seemed relatively small, but if we further compared AT, the performance on the OPT interface significantly outweighed the TLA and the RAN interface. To testify this significance, statistical analysis was then conducted to examine the significance level of difference of CT, AT and PT on 3 interfaces.

Table10. Completion time of the entire task

Interface	Average Completion Time (Standard Deviation) (unit: seconds)*		
	CT	AT	PT
OPT	41.86 (4.73)	15.66 (1.65)	26.20 (3.24)
TLA	45.64 (5.04)	18.97 (2.05)	26.67 (3.19)
RAN	47.70 (4.31)	18.56 (1.83)	29.14 (2.62)

*CT: total completion time; AT: completion time of accessibility-associated task; PT: completion time of proximity-associated task

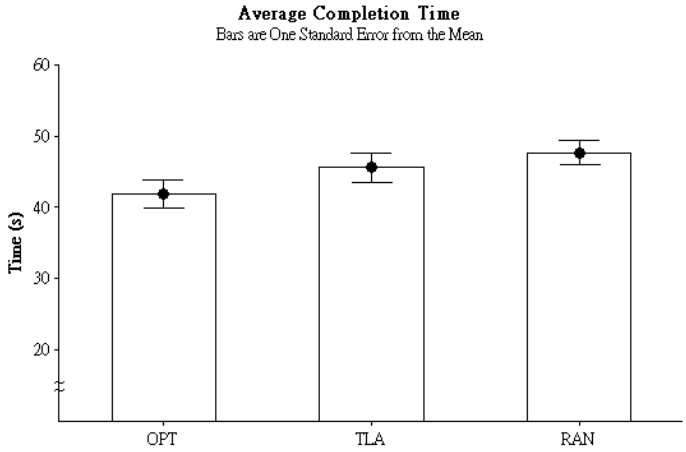


Figure 12. Comparison of total completion time on 3 interfaces

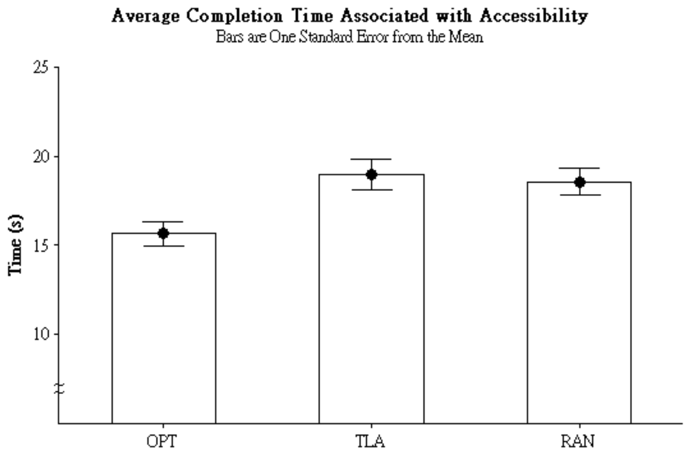


Figure 13. Comparison of completion time associated with accessibility on 3 interfaces

CT, AT and PT were examined by Kolmogorov-Smirnov test to assess their normality. None of them showed significant evidence that the normality assumption was violated. Then they were analyzed by the general linear model in which the interfaces were regarded as fixed factor and the subjects were regarded as random factors. The ANOVA table was shown in Table 11 and the results of Tukey's pair-comparison were shown in Table 12. The statistical results showed that CT and AT were significantly shorter on the OPT interface (95% C.I. >0 and did not contain 0). And PT was significantly longer on RAN interface. Figure 14 showed effect plots of interfaces. Both TLA and OPT interface could improve PT performance significantly, but only OPT interface can significantly improve AT performance on RAN interface and its PT performance was about the same with the TLA's (no significant difference), and therefore only OPT interface could have a significant improvement over RAN interface in terms of total completion time. If we calculated the first 2 components in Equation (7), we would see the difference between the OPT and the TLA interface was 0.26 (3.88 vs. 4.14) while the difference of the last 2 components between the 2 interface was only 0.02 (2.13 vs. 2.11). So the results were compatible to the assumption that the OPT interface would outweigh the TLA interface by its performance in operations associated with accessibility (AT) but PT would be similar between 2 interfaces.

Table 11. ANOVA of CT, AT and PT

Independent Variable	Factors	F-value	P-value	R^2
CT	Interface	F(2, 10)= 28.70	0.000*	95.80%
	Subject	F(5, 10)= 34.10	0.000*	
AT	Interface	F(2, 10)= 44.25	0.000*	95.13%
	Subject	F(5, 10)= 21.36	0.000*	
PT	Interface	F(2, 10)= 19.95	0.000*	95.52%
	Subject	F(5, 10)= 34.67	0.000*	

*significant: $p < .05$

Table 12. Tukey's pair-comparison of CT, AT and PT

Independent Variable	Pairs	95% C.I.
CT	RAN-OPT	(3.696, 7.989)*
	TLA-OPT	(1.638, 5.930)*
	TLA-RAN	(-4.205, 0.88)
AT	RAN-OPT	(1.848, 3.952)*
	TLA-OPT	(2.258, 4.362)*
	TLA-RAN	(-0.642, 1.462)
PT	RAN-OPT	(1.570, 4.315)*
	TLA-OPT	(-0.898, 1.847)
	TLA-RAN	(-3.841, -1.096)*

*significant: $p<.05$

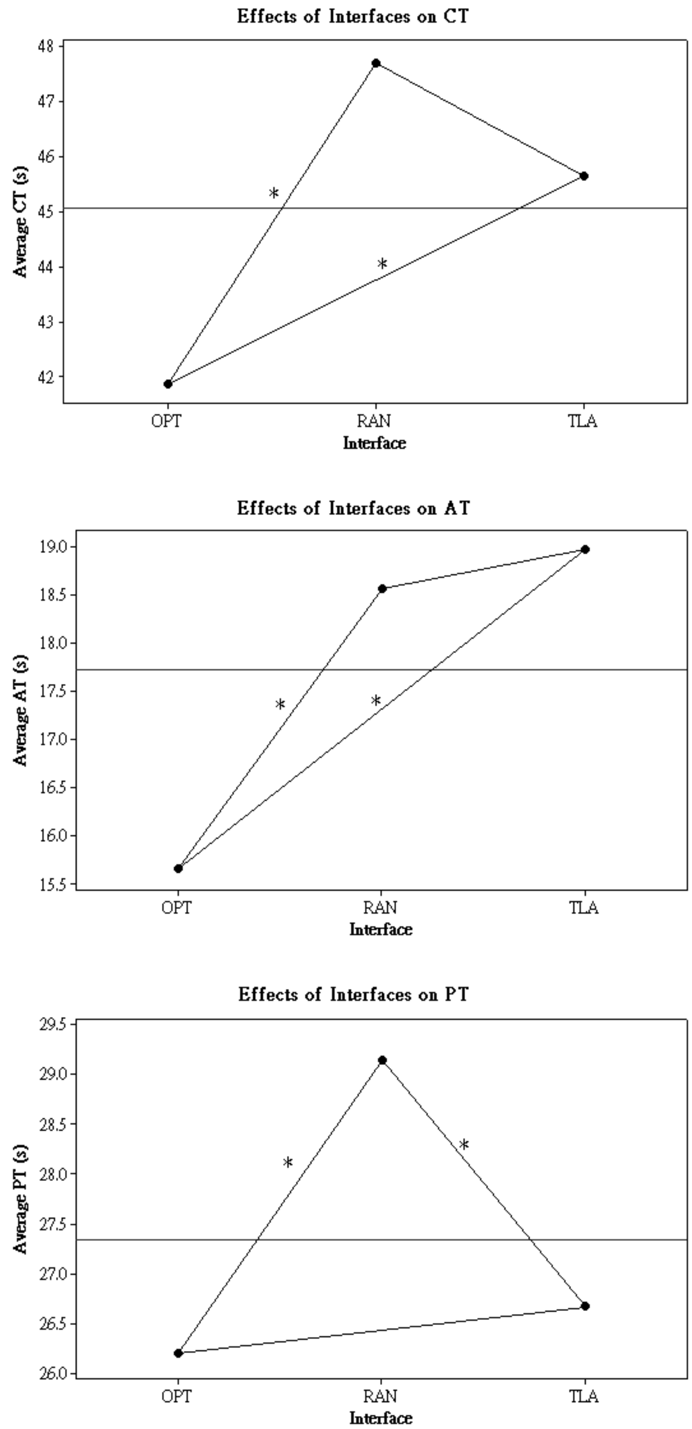


Figure 14. Effects of interfaces on CT, AT and PT (* significance in Tukey's pair-comparison)

4. Discussion

An improved link analysis method based on a modified link table and an optimization-based algorithm was proposed in this study and its effectiveness was validated through a case study and a corresponding experiment. The modified link table contained necessary information for considering both accessibility index and difficulty index in computing overall transitional cost, and the algorithm combined with the modified link value helped finding out optimal interface layout based on the physical features of control elements, relative frequency of usage and the assumed hand origin. Through the case study, the method showed its practicality as well as feasibility, and the experimental result based on the case proved the assumption that, through the improved method, the interface layout can be generated optimally by trading off proximity between elements with accessibility relevant to the hand origin.

The usability, in its nature, involves with many subjective attributes. Besides physical and physiological considerations, psychological characteristics of individuals as well as socio-environmental conditions heavily influence user experience (Dan *et al.* 2008). The interface operation combines cognitive tasks, including visual search, recognition of items, decision making, etc., with physical movements. On one hand, there is indeed a preceding cognitive component before the movements can be executed, and its difficulties of completion varies with a variety of cognitive features such as affordance of the interface (Donald 1999), similarity between items (Yin and Lee 2004), or layout density (Palmiter and Elkerton 1987). Not all of these features can be objectively quantified and the usability based on the same cognitive features can be highly context dependent, affecting by the interaction between tools, problems and individuals (Hornbæk 2006). On the other hand, it appears adequate to separately analyze the time for the movement, estimate the time for cognitive task and add them up for sequential cognitive-manual task since the movement time is predetermined by the Fitts law component (Hoffmann and Lim 1997). Therefore, not a single design technique can be sufficient in evaluating usability thoroughly and comprehensively in that it is unlikely a single method can account for all cognitive and physical aspects mentioned above as well as their interaction with environment. However, the improved link analysis method certainly reduces physiological expenditure because shorter movements in a long term result in less fatigue and in turn a less operation time, which is already validated by the experiment. In addition, the method still keeps the flexibility that the Gestalt-laws or law of proximity can be enforced by grouping sub-elements. Although improved link analysis method does not necessarily improves all aspects in usability concerns, in a sense, link analysis considers functional proximity while optimizes physical distance and layout in order to achieve minimal temporal and physiological cost in using the interface frequently. Other factors such as conceptual compatibility, recognition, affordance, etc, are currently outside the consideration of link analysis. Even so, the improved link analysis method can still help in providing a quantitative evaluation in addition to above usability considerations. A revision of the outcome of link analysis can also be done by usability experts while the method itself still provides basis for comparing alternatives.

The improved method can be applicable to representatively fixed and cognitively simple (i.e. do not require a lot of cognitive work) interfaces by which users perform procedural operations to complete certain tasks for the overall transitional cost can be define more specifically and representatively by the method. The application of the current modified link analysis method becomes more effective when there are many physical movements between the hand and user interfaces. Also for repetitive and continuous operation of interfaces, the improved method can significantly decrease the physical movement demand and alleviate the extent of fatigue as well as its consequent risk, such as injuries and high error rates. The other application of this method can be design of error-prone control interface with high cost of system recovery because the importance is also considered in the link value suggested by this method and can be reflected in the layout design.

Recent link-related studies such as Sears (1993) and Sargent et al. (1997) considered the overall transitional cost as a function of physical features of control elements, the distance between elements and the relative relationship between elements and they also used optimization-based algorithm to obtain alternative layouts. Comparing to their methods, the improved link analysis method suggested in this study took the influence of initiation as well as ending of the operations into consideration and quantified the accessibility using difficulty index in 3D pointing task. Hence two important components, movements between the user and the interface (U-I movements) and within interface movements (W-I movements), can be integrated into one objective function and both frequency and importance are considered in the link value. When the control interface is relatively large and physical movements are still required for operating, the accessibility of control elements with respect to the user's position or initial posture may play a more important role than the proximity between them. In fact, such a large-scale, accessibility-required control interfaces are still and commonly used in many systems such as a real-world nuclear power plant, manufacturing plants and military bases. The system can possibly be controlled by a smaller, computerized program with graphical user interface (GUI) as well, but the necessity of operating an interface, which results in difficulty of both reaching and repetitive operations, and demands more physical movements, do exist.

There are several limitations of current study. First, in the validation experiment we used only six subjects and they were not real operators in the nuclear power plant. In future studies, more subjects and operators in real operation systems need to be recruited. On the other side of the coin, this was a methodology study (it focuses on improving a method), which was different from traditional experimental studies whose contribution and conclusion mainly rely on experimental data and require relatively larger number of subjects. In HCI and human factors studies, to validate new methods or conceptual deign through new methodology, typically no more than 10 subjects would be used and similar number of subjects has been used in previous studies (Hoffmann and Lim 1997, Grobelny *et al.* 2005, Wu and Liu In Press). In addition, the purpose of using BWR in this study was mainly to illustrate one of applications of our method. The interfaces can be BWR, a cellar phone interface, a microwave operation interface, or a car radio interface. Independent of target interface and target user population, the improved method should work in general. Moreover, for a simplified interface of BWR (not a realistic one), it is possible that professional operators would not behave drastically different from those college subjects; and other methodology studies also only used the college students to validate the methods (Brinkman *et al.* 2005, Grobelny *et al.* 2005, Segall *et al.* 2005, Brinkman *et al.* 2008). Therefore, we only selected college students as subjects and let them operate a simplified BWR. Second, for relative small interface without involving many U-I movements, the improved method may not be as influential as being used on the large interface due to decrement of physical demand. The merits of the improved link analysis method can still be expected when it is used to improve small interfaces, but it would be economic to use it on large interface due to the method is more complex than the traditional one. Similar improved link analysis method has been applied to a more realistic interface (microwave control panel) with smaller size in the author's previous study (Lin *et al.* 2008). Third, current method mainly focuses on UIs that users were already very familiar with (users know where each element is allocated); However, for UIs that users do not familiar with and have to visually search the location of elements, new cognitive visual search components need to be added into the current method in future studies. For interface design, the current method can at least provide a quantitative evaluation for overall transitional cost of physical movements, and based on this foundation, other complementary methods (Wu and Liu 2008a, Wu and Liu 2008b, Wu *et al.* 2008c, Wu *et al.* 2008d, Wu and Liu In Press) can also be conducted to assess cognitive efforts needed by the interface so that the cost of these two aspects could be balanced and an optimal interface can be achieved both physically and cognitively.

We are developing new computational methods to improve traditional widely-used user interface design methods. Currently, the computation of overall transitional cost was done by formulated worksheet and it still required a heuristic procedure to find out the optimal layout and consider geometric constraints. The future work can focus on implementing computer software to account for branch-and-bound searching and geometric constraints. Furthermore, more case studies should be conducted to see if the method can be widely used in more complicate interfaces. Finally, the size of the interface definitely may influence the effectiveness of the method. Criterion need to be established to distinguish interfaces which are appropriate and economic for the improved method from those which are more suitable for traditional link analysis. It is also possible that some really big panels need other method, including digital human model, to analyze its usability in that problems in accessibility exceed the scope that can be accounted by Fitts' law and need biomechanical models for evaluation.

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