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Comparative analysis of regular grid based algorithms in the design of graphical control panels

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Abstract. The paper presents comparative investigation of the effectiveness of three algorithms used for optimizing control panel objects' arrangements. We examined two modified classical approaches involving changing of objects' pairs, that is CRAFT, and its simplified version as well as our implementation of the Simulated annealing concept. Their behavior was investigated in experimental simulation studies of two real-life problems: the truck control panel (small number of objects) and the control panel from a nuclear energy plant (big number of items). The statistical analysis of the obtained results showed the supremacy of the proposed version of the simulated annealing algorithm in both case studies.

Keywords: display design · control panels · layout optimization · ergonomics · CRAFT · simulated annealing

1 Introduction

The interaction between a human and a machine is often conducted by means of a graphical interface including either physical or virtual panels with signaling and control components. The optimal layout of these panels lies within the scope of ergonomics and human-computer interactions. McCormick (1976) formulated general principles regarding interface components arrangements that lead to usable solutions. In his opinion the designer should take into account the following criteria: (a) the object's importance, (b) frequency of use, (c) sequences of using objects, and (d) objects' functional similarities. These general recommendations occurred to be quite troublesome in practical applications, therefore a number of tools have been proposed to support the design process. Among them there were attempts to apply formal models from the Facilities Layout Problems (FLP). Generally, classical FLP search for such an arrangement of n objects in n available places that minimizes the general cost which is proportional to distances between objects and depends on the number of transport operations between them. For extensive review see Kusiak and Heragu, 1987 as well as Singh and Sharma, 2006. Two of the general panel design principles (c) and (d) may be analyzed in a similar way once the numerical specifications of objects' relationships are available. Wierwille (1981) proposed statistical methods that can be used for the operationalization of the principles (a) and (b). He named them a first order class models in contrast to rules (c) and (d) described as the second order ones. The first order class models concern relations between the operator and interface components while the second order principles deal with relations between objects.

Numerous optimization approaches in designing interfaces' layouts generally differ in (1) the way of objects' relationships operationalization, (2) included design criteria – the first and/or the second order (3) the way the size and shape of objects are represented. Bonney and Wiliams (1975) proposed a multicriteria and multistage model where objects' relationships were defined subjectively by a designer. Sargent et al. (1997) applied a classical CRAFT algorithm (Armour and Buffa, 1963) in their multistage method for a control panel operated by one person. They used the AHP technique (Saaty, 1980) for determining subjective links between objects including additionally relationships between objects and the operator. Their method also allows for modeling real dimensions of control panel components. Lin and Wu (2010) use similar to Sargent et al. (2007) modification of links data but add also the criterion of time needed to operate the panel based on the Fitts's law (1954). They employed the Branch and Bound algorithm for optimization which was proposed in the FLP area by Gavett and Plyter (1966).

Apart from classical algorithms there are also proposals based on artificial intelligence like genetic algorithms, ant colony or particle swarms. Hani et al. (2007), for instance, applied ant colony algorithm. A similar approach was presented by Shengyuan et al. (2013). In the former case links represented only the frequency of use while in the latter article the relationships reflected both the importance of objects and sequences of use. In both cases, shapes and sizes of components were not taken into account.

Despite multiple papers in this area it is difficult to find studies presenting comparisons of algorithms applied for searching optimal control panel or interface layouts. Thus, the main goal of this research is to compare the effectiveness of two relatively simple classical algorithms and our implementation of the simulated annealing concept. Their performance is examined in two, real-life examples. All algorithms operate on the regular grid and allow for modeling areas of individual components. Our approach, just like Sargent et al. (1997) and Lin and Wu (2010), includes both the first and the second order criteria.

2 Method

2.1 Applied algorithms

For comparisons we used a classical version of the CRAFT algorithm originally presented by Buffa et al. (1964). The idea of this approach consists in making changes in objects locations by pairs as long as they improve the goal function value (GFV). The algorithm starts from the random objects' arrangements on a regular grid.

We also used a simpler than CRAFT algorithm also based on pairs swaps (Pairs). We just excluded the outer loop from CRAFT and, thus, the appropriate pairs' changes are stopped after only one run of the algorithm.

Our Simulated Annealing (SimAnn) algorithm was implemented according to the general idea described by Kirkpatrick et al. (1983). They recommended that in the first step of the algorithm one should accept worse solutions with the probability of 0.8. Starting from this assumption and preliminary estimation of the delta according to the procedure similar to Singh and Sharma (2008) we calculated Ti. The epoch length was set as a value proportional to the number of objects $k \times N$ such as in papers of Wilhelm and Ward (1987) or Heragu and Alfa (1992). The cooling scheme was specified as in Heragu and Alfa (1992), that is $T_j = r \times T_{j-1}$,, where r = 0.9. The final temperature was determined by a number of predefined steps i as $T_f = 0.9^{(i-1)} \times T_i$ Parameter k and i were obtained by preliminary simulations for the examined case studies and amounted to i = 100 and k = 5. Finally, the T_f for the first and the second case study was set at 50 and 20000 respectively.

In all algorithms, there was a possibility of blocking specific objects in certain places of the regular grid.

2.2 Relationships matrix modifications

Two modifications of the relationships matrix were made in our approach. First, as it was proposed by Sargeant et al. (1997), we added the first order links (operator-objects) to the original matrix containing the second order relationships (object-object). The additional data represented assessments of all objects in relation to the most important or most frequently used item which is located in front of the operator.

Secondly, we added the possibility of including the areas occupied by individual components in conducted analyses. For this purpose, each object was modeled by the appropriate number of regular grid segments proportional to its real dimensions. One of the segments of a given object was set as the main one and all remaining were linked with it. Such an approach allowed for the inclusion of areas covered by objects but not their shapes.

2.3 Experimental design

The presented above three algorithms along with described modifications were applied for the analysis of two real-life control panels considerably different in their complexity. The first project concerns truck driver informative panel layout. The solution to this problem was ordered by a company manufacturing such vehicles in Poland. The panel consisted of eight items: (1) Speedometer, (2) Tachometer, (3) Air pressure, (4) Oil pressure, (5) Water temperature, (6) Oil temperature, (7) Clock and Time of driving, (8) Diagnostic screen. It was assumed that the panel should be in the form of a digital, graphical display located at the center of the dashboard with all components arranged in one row. The sequences of objects' uses and their importances were determined by means of a questionnaire administered to 20 truck drivers. The drivers' opinions were expressed on five step scale. Since the speedometer was considered as the most important object (on the same scale), we added appropriate values to the relationships in the first row of the matrix. The final results rounded to the integer numbers are put together in Table 1. The shapes and sizes of the components were not defined so each segment of the regular grid represented one object.

Object	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)	×	10	8	6	7	1	5	1
(2)	3	×	5	3	3	0	3	0
(3)	0	5	×	3	3	3	0	0
(4)	0	5	3	×	3	0	0	0
(5)	5	5	5	3	×	3	0	0
(6)	5	5	3	5	3	×	0	0
(7)	5	0	0	0	0	0	×	0
(8)	0	0	0	0	0	0	0	×

Table 1. The relationships matrix including the first and the second order data for the truck panel layout case study.

The second example was taken from the paper of Sargent et al. (1997) and consisted of considerably bigger number of items than the first one. The original relationships data were modified by adding dummy objects to reflect the components sizes. Pilot tests showed that the links strengths between these additional items should be bigger than the biggest existing relationship value. We set it at the level of 500. Because the object 1 has the highest priority, its location was fixed in the center of the layout. The grid dimensions and the original null objects were the same as in the original work.

2.4 Simulation procedure

In both cases the experimental simulation procedure was identical. We ran 100 times each of the three described earlier algorithms. Every iteration started from a random arrangement of segments. In the second case study the most important objects with the number 1 were placed in the center of the grid and blocked. In the truck panel case it was assumed that all objects are within a central visual field, so the most important component was not fixed. The goal function value was recorded in for every individual simulation.

3 Results

3.1 Truck panel

The basic descriptive statistical data regarding the truck panel layout are demonstrated in Table 2.

Algorithm	Min	Max	Mean	*MSE	**SD

Pairs	266	279	271	0.474	4.74
CRAFT	266	279	269	0.342	3.42
SimAnn	266	266	266	×	×

[*] MSE – Mean Standard Error, [**] SD – Standard Deviation

Table 2. Basic descriptive statistics for the truck panel layout case study.

As it can be observed, the best layout with the GFV = 266 could be obtained using any of the examined algorithms in 100 repetitions. The best performance was recorded for the SimAnn algorithm, where the best value was found in each iteration. The worst average GF values were registered for the simple Pairs procedure. Mean standard errors and standard deviations were smaller for the CRAFT than for the Pairs algorithm. The best layout configuration is illustrated in Figure 1.

6	**4**	**3**	**5**	**2**	**1**	**7**	**8**

Fig. 1. The best layout for the truck panel layout case study (GFV= 266)

A standard one way Analysis of Variance showed that the differences in mean values for the algorithms are statistically significant at the level of 0.05. The ANOVA results are presented in Figure 2.

Fig. 2. Mean goal function values for the truck panel layout; $F(2, 297) = 46$, $p < 0.00001$. Vertical bars denote 0.95 confidence intervals.

The Fischer LSD post hoc analysis revealed significant differences between all pairs of algorithms ($\alpha = 0.05$).

3.2 Nuclear power plant

Descriptive statistical data concerned with the second case study is presented in Table 3. Here again, the best average goal function values as well as the best solutions were obtained by means of the SimAnn algorithm. The worst mean values and solutions with minimal GFVs were observed for the Pairs algorithm. The Simulated annealing algorithm exhibited also the smallest values of standard deviation which may indicate that it provides consistently good solutions.

Algorithm	**Min**	**Max**	**Mean**	***MSE**	****SD**
Pairs	59101	83294	68634	424	4240
CRAFT	54969	78585	67504	385	3852
SimAnn	51955	58137	54876	131	1314

* MSE – Mean Standard Error, ** SD – Standard Deviation

Table 3. Basic descriptive statistics for the nuclear energy plant control panel layout.

The best found solution for the nuclear plant control panel is shown in Figure 3.

16	13	13	8	17	17	2	5	5	5	5	3	4	12	12	12	21	22	23	26
16	10	8	8	19	19	2	7	7	1	1	3	4	4	15	15	22	22	22	25
10	10	8	9	18	2	2	2	7	1	1	3	14	4	11	22	22	22	22	22
24	10	20	9	18	2	2	2	7	6	6	14	14	14	11	11	22	22	22	27

Fig. 3. Best layout obtained by Simulated annealing algorithm for the nuclear energy plant control panel. GFV = 51 955.

For the comparison purpose we reproduced the original best objects' configuration obtained by the CRAFT algorithm in the work of Sargent et al. (1997). The result is given in Figure 4.

25	21	19	19	20	12	12	5	5	5	5	6	6	4	4	11	15	15	22	23
16	16	9	9	8	8	12	7	7	1	1	2	4	4	11	11	22	22	22	22
26	18	18	8	8	10	10	7	7	1	1	2	2	3	14	14	22	22	22	22
27	17	17	13	13	10	10	2	2	2	2	2	3	3	14	14	22	22	22	24

Fig. 4. Original best layout for the nuclear power plant layout (Sargen et al., 2007). GFV= 69 484.

After inclusion of our relationships matrix modifications, the goal function for this solution amounted to GFV= 69 484 which is markedly worse than our best layout. Again, we apply the standard one way ANOVA which showed significant differences between average goal function values for the algorithms: $F(2, 297) = 507$, $p < 0.00001$. The results are illustrated in Figure 5.

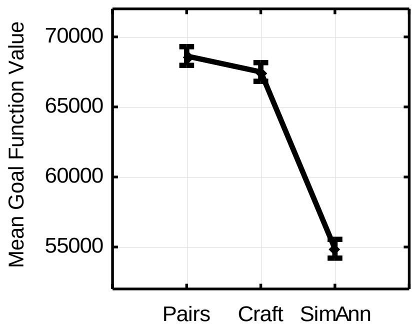

Fig. 5. Mean goal function values for the nuclear energy plant control panel layout; $F(2, 297) = 507$, $p < 0.00001$. Vertical bars denote 0.95 confidence intervals.

Also in this case the Fischer LSD post hoc analysis showed statistically meaningful ($\alpha = 0.05$) differences between all pairs of algorithms.

4 Discussion And Conclusions

In this research we analyzed two cases that differed considerably in terms of complexity. Despite that in both examples the applied approaches had similar properties. Firstly, the presented here modifications of the relationships' matrix enable, in a natural way, to include information about objects sizes in simple regular grid analyses. This way of preparing data allows for obtaining in a regular grid coherent objects structures without involving additional constrains. This concept probably offers greater flexibility of the generated solutions in relation to approaches that require imposing additional limitations. Perhaps thanks to this feature, all the best solutions in the second case study are better than the best solution obtained originally by means of the standard CRAFT with fixed locations of the same objects' segments. This outcome was observed regardless of the algorithm applied.

The second major result of the present study is concerned with the significant supremacy of the simulated annealing algorithm over the other investigated here. It seems that this type of metaheuristic suits the data structure of man-machine interface problems very well. It is especially true in big problems such as the nuclear power plant control panel. The benefits measured by the decrease both in the mean and minimal goal function values are meaningful in relation to the commonly applied in such problems CRAFT algorithm. In the second case study, the percentage gain amounted to 19% for average goal function value and 5% for the best solutions.

Some limitation of employing the simulated annealing algorithm is its efficiency. Though in this study we did not precisely recorded computation times, but we observed quite big differences between applied algorithms. Approximate times for the single simulation in the second case study equaled about 10 seconds for the simple pairs' changes, 2 minutes for CRAFT and, as much as 5 minutes for simulated annealing. Therefore, in case of bigger problems, repeating the simulated annealing or even CRAFT procedures may not be feasible. In such situation one may use the markedly faster pairs' changes algorithm. It provided the worst solutions but the difference in mean goal function values for the second case study in relation to classical CRAFT amounted barely 2%.

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