Problem Statement for Heat Pipe-Constrained Component Layout Optimization Competition in CEC2022

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Abstract

In this report, the heat pipe-constrained component layout optimization (HCLO) problem is introduced for providing participants a better insight to the background of this competition. The mathematical model of the HCLO problem is constructed as a continuous constrained single-objective optimization problem. In the following, four public test layout problems are defined and presented with specific parameter settings. The evaluation codes for the objective and constraints of these problems have been well-prepared, which can be accessed in our competition page at https://idrl-lab.github.io/CEC2022-HCLO. The allowable maximum number of function evaluation is set as $5000D$ where D means the dimension of design variables. The performance evaluation of the proposed evolutionary algorithms only depends on the objective function when all the constraints have been satisfied. It is desirable for participants to develop layout search algorithms that can find the layout design scheme with lower objective and simultaneously less computational cost.

1 Introduction

The performance of electronic devices is significantly influenced by the placement of its components. For example, an increasing number of electronic components are required to be installed within a small size of device space (such as print-circuit boards), thus easily causing a severe heat concentration. An irreversible device damage would probably happen under over-high temperature if their positions are not carefully arranged. Therefore, it raises an important practical engineering-driven optimization problem, the component layout optimization (CLO) problem [1–3]. The objective of this problem is to maximize the thermal performance by optimizing the layout scheme of components while satisfying some necessary design constraints (including non-overlapping constraints, system centroid constraint, etc.). To obtain the global optimal component layout design, population-based evolutionary algorithms show their unique advantages over than gradient-based algorithms. However, the complexity in such problems still poses great challenges to common evolutionary optimization algorithms.

Firstly, taking position coordinates as design variables, the CLO problem can easily become a high-dimensional optimization problem with the number of components increases. Secondly, a huge number of complex constraints should be strictly satisfied. One type of basic geometric constraint is the spatial non-overlapping constraint between components or between the container and components, which requires that no overlap exists between any two objects. Thirdly, there may exist two or more distinct component layout design schemes corresponding to the same or similar performance, which makes the CLO a multimodal optimization problem. All these points make the CLO problem intractable in efficiently and effectively searching optimal or suboptimal layout solutions using common evolutionary algorithms, which highly hampers their industrial applications. The aim of this competition is to promote the research on continuous constrained single-objective optimization problems and hence solve complicated real-world application problems.

In this competition, one typical layout design scenario, the heat pipe-constrained component layout optimization (HCLO) problem, is carefully selected and simplified from the real-world engineering layout application. Four HCLO problems are designed and provided for public performance evaluation of the proposed layout algorithms. Another private HCLO problem has been prepared specially for final fair evaluation of the algorithms submitted by participants, which will be conducted by organizers. Note that these problems have different number of components, thus maintaining different optimization scales and complexity. The aim of this report is to help participants understand the background of this competition and the meaning of layout problems, thus eliminating some potential confusion. However, from the perspective of algorithm implementation, it is optional for participants to read this report since all evaluation codes of four layout examples have been well-prepared and can be easily treated as black-box optimization problems.

In the following contents, the HCLO problem and its mathematical formulation are mainly introduced in Section 2. The detailed information about the layout domain and components in different layout test problems are illustrated in Section 3.

2 Problem Description and HCLO model

In this section, the HCLO problem is introduced, and then the HCLO model is formulated with defining proper design variables, layout constraints, and the optimization objective.

2.1 Problem description

Driven by the engineering application of determining the optimal satellite payload placement in the DFH-4 bus, the HCLO problem is proposed, illustrating a new kind of component layout optimization problem.

DFH-4 bus is an international advanced large telecommunications satellite platform for the high

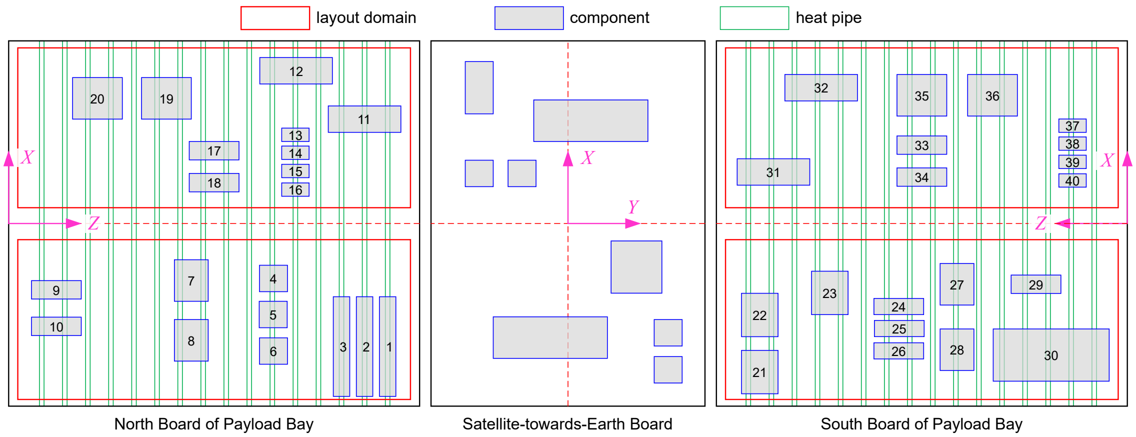


Figure 1: The illustration of satellite payload placement of DFH-4 bus

capacity broadcast, regional mobile communication, etc., aiming for international and domestic commercial communication satellite markets.[1] With some simplification, a two-dimensional (2D) view of bearing boards of DFH-4 satellite payload bay is displayed in Figure 1. There are three main boards, including one satellite-towards-Earth (STE) board and two side boards, in this payload bay. The plotted Cartesian coordinate system $O - XYZ$ illustrates their spatial relationship. The STE board means that this plane always points to Earth when the satellite is flying in its space orbit. On this board, antennas are usually installed on the outer surface of the STE board while signal receivers or transmitters on its inner surface, as well as some components with low heat-generating power. Two side boards, namely the north and south board, are utilized to arrange some components with high heat power since most of the generated heat by components is dissipated through these two boards outside the satellite. To be more specific, heat is firstly conducted by heat pipes embedded in two side boards to their outer surfaces and then radiated to the cold deep space (constant at 4K). It is assumed that layout components on the STE board have been placed in their right position in advance. Therefore, the task layout problem is established to address how to properly arrange the positions of components on the north and south board with meeting satellite performance requirements on the heat dissipation and system static stability.

As shown in Figure 1, this 3D layout task can be simplified to a 2D layout optimization problem identifying X and Z coordinates of components on two side boards without considering their spatial intrusion with other satellite parts in the Y-axis direction. Each board is divided into two feasible layout domains, denoted by red rectangles, where electronic devices (components), represented by blue shaded rectangles, are restricted to be placed without any protrusion. The thin green bar denotes the heat pipe, which efficiently absorbs the heat generated by components and quickly reaches a balanced heat dissipation state. The design requirements on thermal performance and mass characteristic for satellite payload placement of DFH-4 are mainly discussed in this paper, including:

[1]Krebs, Gunter D. "DFH-4 Bus". Gunter's Space Page. Retrieved December 22, 2021, from https://space.skyrocket.de/doc_sat/ch__dfh-4.htm

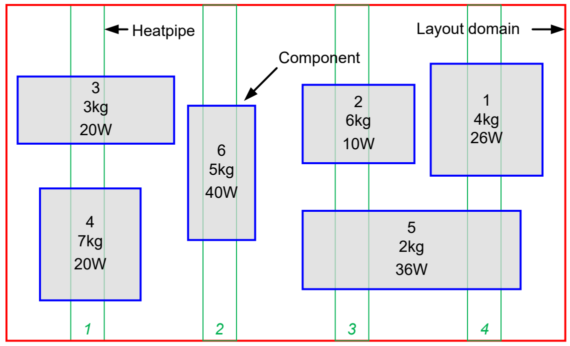


Figure 2: The illustration of the heat pipe-constrained component layout optimization (HCLO) problem

- The system centroid of satellite payload bay should approach the expected one or satisfy the given specific centroid range.
- Components are required to overlay on the surface of heat pipes to guarantee that the generated heat can be directly dissipated by heat conduction.
- The total heat power dissipated by every single heat pipe, which depends on components covering its surface, cannot exceed its maximum load capacity.
- The dissipated power over different heat pipes in one board should be balanced, that is, as close as possible such that the uniformity of temperature distribution over the entire board can be maximized and heat concentration can be avoided.

Following the aforementioned assumptions, the HCLO problem is defined as one typical layout design scenario where the thermal performance based on heat pipes is maximized by optimizing the placement of components, simultaneously meeting the static stability constraint.

2.2 The HCLO model

The mathematical model of the HCLO problem is constructed in this subsection. Notice that three assumptions have been made in advance. First, components are assumed to be rigid cuboids with a uniform mass distribution, which means their centroids are coincident with their geometric centers. Second, components that are required to be placed on these two side boards have been a priori allocated to different layout domains according to some engineering practice. It means that swap operation of components between different layout domains is not allowed during optimization. Third, components are restricted to be placed orthogonally, and rotation of 90 degrees is also not allowed during the optimization. The last two assumptions reduce the design space and thus lower the optimization difficulty to some extent. Therefore, this HCLO problem can be established as a 2D layout optimization model, which is simply illustrated using Figure 2 without loss of generality.

2.2.1 Design variables

For computational convenience, a 2D Cartesian coordinate system $O - xy$ is defined, where x-axis is aligned with the horizontal direction and y-axis with the vertical direction. Heat pipes are evenly distributed along the x-axis direction to realize better heat transfer and spread heat over the domain uniformly. Taking geometric centers as reference points, the placement of components can be easily determined using their 2D position coordinates (x_i, y_i). On the basis of this, design variables of the HCLO model can be represented as:

$$\boldsymbol{X} = \{(x_i, y_i)|i = 1, 2, ..., N_c\} \tag{1}$$

where i denotes the i^{th} component and N_c means the number of components to be placed; $\boldsymbol{X}$ represents the component layout scheme, which can uniquely define the placement in their allocated layout domain.

It can be easily concluded that the number of design variables is $2N_c$. As the number of components N increases to the magnitude of hundreds, the HCLO problem will become high-dimensional, greatly increasing the complexity of the search space and thus the difficulty of identifying its optimal solution.

2.2.2 Layout constraints

Four types of layout constraints should be satisfied to accommodate satellite thermal performance and system mass characteristics: the non-overlapping constraint, system centroid constraint, component-heat pipe overlapping constraint, and heat dissipation capacity constraint.

(1) Non-overlapping constraint

The non-overlapping constraint, as a basic spatial geometry constraint, demands no overlap between different components and between components and the layout domain. The overlap volume should be strictly equal to zero to guarantee the feasibility of one layout scheme. Hence, the non-overlapping constraint can be expressed as:

$$g_1(\boldsymbol{X}) = \sum_{i=0}^{N_c-1} \sum_{j=i+1}^{N_c} \Delta V_{ij} \leq 0 \tag{2}$$

where $\Delta V_{ij}(i, j > 0, i \neq j)$ refers to the amount of intersection area between component i and j; when $i = 0$, object i denotes the layout domain and ΔV_{ij} means the amount of protrusion area of component j out of the layout domain.

The overlap area between rectangles placed orthogonally can be easily calculated analytically in this case. For more complex geometries, it is an efficient approach to analytically and explicitly measure the amount of overlap by distance using the phi-function method [4].

(2) Static stability constraint

Static stability constraint here represents the system centroid constraint, where the mass center of satellite payloads along the y-axis direction in the $O - xy$ system (i.e. the X-axis centroid in the $O - XYZ$ system) is required to be controlled within its permissible range. In other words, the system centroid deviation should be limited in its predefined offset. Note that this constraint can also be modeled as the objective that the real y-axis system centroid y_c is expected to be as close as the expected one. It means that the system centroid error should be minimized. Following its definition, we can formulate this constraint as:

$$g_2(\boldsymbol{X}) = |y_c - y_e| - \delta y_e \leq 0 \tag{3}$$

where y_c and y_e are the real and expected y-axis system centroid, respectively; δy_e is the maximum allowable centroid deviation.

(3) Component-heat pipe overlapping constraint

The component-heat pipe overlapping constraint is defined as another geometry constraint, requiring that the foot area of components must be placed on top of any one or several heat pipes horizontally to ensure effective heat conduction. Therefore, in a 2D projection view, components should intersect with several bar-shaped heat pipes geometrically. To guarantee a safe assembly operation and an efficient heat transfer, the width that is occupied on any one heat pipe by each component should be controlled as a larger value than the threshold. The threshold width d_{com}^{hp} is set as the width of the heat pipe in this case, which means that only the situation where the component cross over the entire heat pipe can be regarded as one valid heat pipe occupation. Thus, this constraint can be represented as:

$$g_3(\boldsymbol{X}) = \sum_{i=1}^{N_c} |\max(d_i, 0)| \leq 0 \tag{4}$$

where d_i denotes the distance away from its nearest heat pipe when component i does not intersect with any one heat pipe under the assumption of the valid heat pipe-occupation. This distance is analytically calculated using the adjusted phi-function approach as introduced in [4]. As long as the component can validly cross over at least one heat pipe, this distance value would maintain zero. For example, component 5 in Figure 2, which has a large horizontal length, can readily satisfy this constraint under arbitrary placement. Following their mutual relationship, the number of heat pipes occupied by one component can only switch between two possible options. However, its value depends on its specific position.

(4) Heat dissipation capacity constraint

Each heat pipe has its maximum heat dissipation capability, defined as the maximum load power P_{max}^{hp}. Heat dissipation capacity constraint describes that the actual total power dissipated by each heat pipe cannot exceed its maximum load capacity. The total dissipated power by one heat pipe is determined by accumulating the heat power of components that crosses over this heat pipe. When the heat generated by one component is dissipated through several heat pipes, that is, one component occupies multiple heat pipes simultaneously, it is assumed that the component power is averaged and then added to the real load calculation of each of its occupied heat pipes. Hence, this constraint can be written as:

$$g_4(\boldsymbol{X}) = P_j^{hp} = \sum_{i \in \mathcal{H}_j} P_i / n_i^{hp} \leq P_{max}^{hp} \qquad \forall j = 1, 2, ..., N_{hp} \tag{5}$$

where P_j^{hp} is the real load power of the j^{th} heat pipe; $\mathcal{H}_j$ represents the set of components that occupy the j^{th} heat pipe; P_i and n_i^{hp} denotes the heat power of component i and the number of heat pipes occupied by component i, respectively; N_{hp} is the total number of heat pipes. Note that n_i^{hp} varies with the position of component i and should be updated after its movement according to the rule of valid heat pipe-occupation. When investigating DFH-4-like cases, heat pipes cross over the entire board along the X-axis, that is, two layout domains. The calculation of real heat pipe load power should be performed based on the placement of components in these two layout domains simultaneously.

2.2.3 Optimization objective

Since the layout design goal, in this case, is to improve the uniformity of the temperature field based on heat pipes, the optimization objective is set to minimize the maximum real load power of heat pipes in one layout board. Thus, the objective can be formulated as:

$$f(\boldsymbol{X}) = \max_{j=1,2,...,N_{hp}} P_j^{hp} \tag{6}$$

.

When considering the DFH-4 case involving two side boards, this objective is extended as the summation of their respective maximum real load power of heat pipes in different boards. It can be represented as $f(\boldsymbol{X}) = \max_{j=1,2,...,N_{hp}^N} P_j^{hp_N} + \max_{j=1,2,...,N_{hp}^S} P_j^{hp_S}$, where N and S denote the north and south board, respectively.

2.2.4 Formulation of the HCLO model

With the aforementioned definition of design variables, constraints and objective, the HCLO model can be formulated as follows:

$$\begin{cases} \text{find} \quad \boldsymbol{X} \\ \min \quad f(\boldsymbol{X}) = \max\limits_{j=1,2,...,N_{hp}} P_j^{hp} \\ \text{s.t.} \quad \begin{cases} g_1(\boldsymbol{X}) = \sum\limits_{i=0}^{N_c-1} \sum\limits_{j=i+1}^{N_c} \Delta V_{ij} \leq 0 \\ g_2(\boldsymbol{X}) = |y_c - y_e| - \delta y_e \leq 0 \\ g_3(\boldsymbol{X}) = \sum\limits_{i=1}^{N_c} |\max(d_i, 0)| \leq 0 \\ g_4(\boldsymbol{X}) = P_j^{hp} \leq P_{max}^{hp} \quad \forall j = 1, 2, ..., N_{hp} \end{cases} \end{cases} \tag{7}$$

.

Let us investigate this problem more deeply from the view of optimization. First, the dimension of design variables varies twice with the number of components, easily making the HCLO problem a large-scale one. Second, despite a few constraint types, the number of constraints that need to be satisfied behind is huge. For example, the non-overlapping constraint requires that any two objects need to be prevented from the intersection, thus including $N_c(N_c + 1)/2$ specific non-intersection constraints if N_c components are placed in one layout domain. Besides, the feasible region of design space is quite small as constraints can scarcely be satisfied at the same time in most randomly generated layout schemes. When one component translates in some direction for the non-intersection purpose with another one, it is possible to intrude with the third one or violate the valid heat pipe-occupation rule. The complexity of constraints further makes this problem intractable. Third, by seeing the objective regardless of design variables and constraints, the HCLO problem is a kind of combinatorial optimization. There may exist two or more distinct component layout schemes with the same objective value, displaying the feature of multimodal optimization. For example, exchanging positions of components 1 and 2 in Figure 2 will not change the objective. In a word, the proposed HCLO case is a continuous constrained multimodal single-objective optimization problem with great complexity.

3 Four Test Problems

In this competition, four test problems with different complexity are provided for performance evaluation of layout search algorithms. In the first problem, there are 6 components to be placed in one layout domain. The number of components to be arranged in Problem 2 increases to 15, which makes it a 30-dimensional optimization problem. In Problem 3, two layout domains are considered with the need of placing 40 components in one layout board. A different thing from the previous two problems is that although components are allocated in two layout domains without overlap between each other, the objective function involving heat dissipation should be considered and calculated as a whole as heat pipes cross over these two layout domains. In problem 4, 90 components are defined to be placed in two side boards, that is, four layout domains. Even if the thermal performance of two boards can be calculated independently, the system centroid of layout design depends on the placement of all components. Besides, compared with Problem 3, the number of design variables increases from 80 to 180.

3.1 Problem 1: A layout example with 6 components in one layout domain

- Layout domain: $x \in [-40, 40]$, $y \in [-25, 25]$
- Heat pipes:
  - number: 4
  - width: 5

Table 1: Characteristics of 6 layout components in Problem 1

No.	w(mm)	h(mm)	m(kg)	P(W)
1	15	9	2.5	20
2	20	5	1.3	13
3	10	7.5	2	16
4	14	8	3.5	26
5	8	6.5	1.8	6
6	15	6	3	10

  - maximum load power: $P_{max}^{hp} = 30$ W.
- Components:
  - number: 6
  - size, mass, heat power: see Table 1.
- Expected y-axis system centroid: $y_e = 0$ mm
- The permissible maximum centroid deviation: $\delta y_e = 0.5$ mm
- Dimension: $D = 12$
- Maximum number of function evaluation: 5000 * 12

3.2 Problem 2: A layout example with 15 components in one layout domain

- Layout domains: $x \in [100, 900]$, $y \in [25, 475]$
- Heat pipes:
  - number: 6
  - width: 30
  - maximum load power: $P_{max}^{hp} = 60$ W.
- Components:
  - number: 15
  - size, mass, heat power: see Table 2.
- Expected y-axis system centroid: $y_e = 250$ mm
- The permissible maximum centroid deviation: $\delta y_e = 5$ mm
- Dimension: $D = 30$
- Maximum number of function evaluation: 5000 * 30

One layout example of Problem 2 is provided in Figure 3 for visualization.

Table 2: Characteristics of 15 layout components in Problem 2

No.	w(mm)	h(mm)	m(kg)	P(W)
1	45	75	4.6	10.5
2	60	30	6.3	25
3	125	23	6.6	18
4	60	30	6.3	25
5	45	75	4.6	10.5
6	160	42.5	10	28
7	180	39	8	25
8	74	52.5	5	10
9	160	37.5	7	30
10	103	41.5	5.5	5
11	286	37.5	2	34
12	74	52.5	5	10
13	160	37.5	7	30
14	100	30	3.5	15
15	100	30	3.5	15

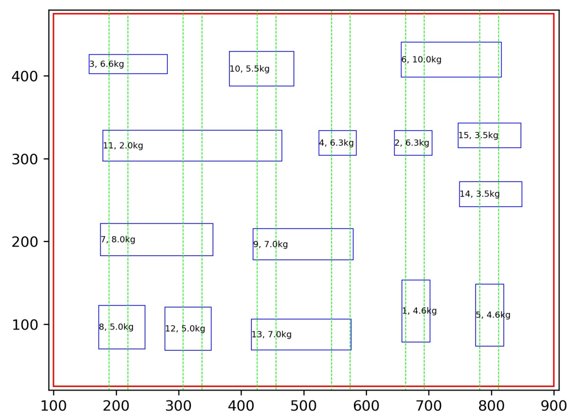


Figure 3: One layout example of Problem 2

3.3 Problem 3: A layout example with 40 components in two layout domains

- Layout board: $x \in [0, 2000]$, $y \in [-1000, 1000]$
  - domain 1: $x \in [100, 1900]$, $y \in [-950, -50]$
  - domain 2: $x \in [100, 1900]$, $y \in [50, 950]$
- Heat pipes:
  - number: 16
  - width: 30
  - maximum load power: $P^{hp}_{max} = 120$ W.

Table 3: Characteristics of 40 layout components in Problem 3

No.	w(mm)	h(mm)	m(kg)	P(W)	domain	No.	w(mm)	h(mm)	m(kg)	P(W)	domain
1	200	50	6.5	70	1[*]	21	200	50	6.5	70	2[†]
2	200	50	6.5	70	1	22	200	50	6.5	70	2
3	200	50	6.5	70	1	23	200	50	6.5	70	2
4	200	50	6.5	70	1	24	200	50	6.5	70	2
5	200	50	6.5	70	1	25	200	50	6.5	70	2
6	280	60	4.6	56	1	26	280	60	4.6	56	2
7	280	60	4.6	56	1	27	280	60	4.6	56	2
8	280	60	4.6	56	1	28	280	60	4.6	56	2
9	120	50	3	10	1	29	120	50	3	10	2
10	120	50	3	10	1	30	120	50	3	10	2
11	180	75	4	36	1	31	180	75	4	36	2
12	180	75	4	36	1	32	180	75	4	36	2
13	180	75	4	36	1	33	180	75	4	36	2
14	180	75	4	36	1	34	180	75	4	36	2
15	180	75	4	36	1	35	180	75	4	36	2
16	100	100	2.8	15	1	36	100	100	2.8	15	2
17	100	100	2.8	15	1	37	100	100	2.8	15	2
18	100	100	2.8	15	1	38	100	100	2.8	15	2
19	100	100	2.8	15	1	39	100	100	2.8	15	2
20	100	100	2.8	15	1	40	100	100	2.8	15	2

[*] 1 denotes the lower layout domain in the board.
[†] 2 denotes the upper layout domain in the board.

- Components:
  - number: 40
  - size, mass, heat power: see Table 3.
- Expected y-axis system centroid: $y_e = 20$ mm
- The permissible maximum centroid deviation: $\delta y_e = 5$ mm
- Dimension: $D = 80$
- Maximum number of function evaluation: 5000 * 80

One layout example of Problem 3 is provided in Figure 4 for visualization.

3.4 Problem 4: A layout example with 90 components in four layout domains

- Layout board (north/left): $x \in [0, 2000]$, $y \in [-1000, 1000]$
  - domain 1: $x \in [100, 1900]$, $y \in [-950, -50]$
  - domain 2: $x \in [100, 1900]$, $y \in [50, 950]$
- Layout board (south/right): $x \in [0, 2000]$, $y \in [-1000, 1000]$

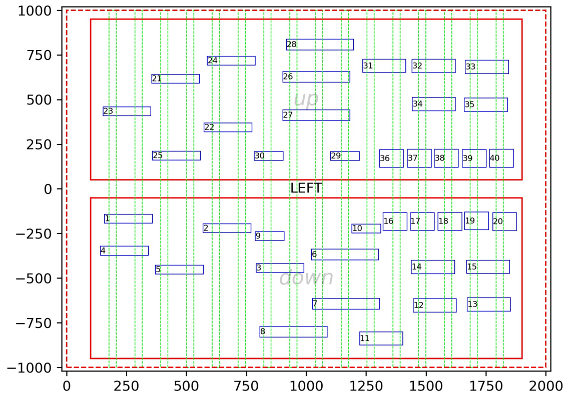


Figure 4: One layout example of Problem 3

- domain 3: $x \in [100, 1900]$, $y \in [-950, -50]$
- domain 4: $x \in [100, 1900]$, $y \in [50, 950]$

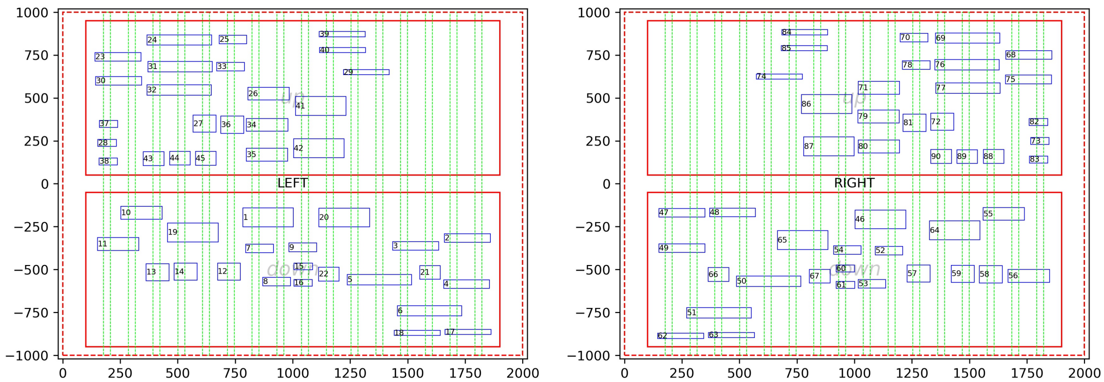
- Heat pipes:
  - number: 16
  - width: 30
  - maximum load power: $P^{hp}_{max} = 120$ W.
- Components:
  - number: 90
  - size, mass, heat power: see Table 4.
- Expected y-axis system centroid: $y_e = 0$ mm
- The permissible maximum centroid deviation: $\delta y_e = 5$ mm
- Dimension: $D = 180$
- Maximum number of function evaluation: 5000 * 180

One layout example of Problem 2 is provided in Figure 5 for visualization.

Table 4: Characteristics of 90 layout components in the north and south board in Problem 4

No.	w(mm)	h(mm)	m(kg)	P(W)	domain	No.	w(mm)	h(mm)	m(kg)	P(W)	domain
1	220	110	10	42.5	1*	46	220	110	10	42.5	3‡
2	200	50	6.5	70	1	47	200	50	6.5	70	3
3	200	50	6.5	70	1	48	200	50	6.5	70	3
4	200	50	6.5	70	1	49	200	50	6.5	70	3
5	280	60	4.6	55	1	50	280	60	4.6	55	3
6	280	60	4.6	55	1	51	280	60	4.6	55	3
7	120	50	3	26	1	52	120	50	3	26	3
8	120	50	3	26	1	53	120	50	3	26	3
9	120	50	3	26	1	54	120	50	3	26	3
10	180	75	4	32	1	55	180	75	4	32	3
11	180	75	4	32	1	56	180	75	4	32	3
12	100	100	2.8	15	1	57	100	100	2.8	15	3
13	100	100	2.8	15	1	58	100	100	2.8	15	3
14	100	100	2.8	15	1	59	100	100	2.8	15	3
15	80	40	2.6	6.5	1	60	80	40	2.6	6.5	3
16	80	40	2.6	6.5	1	61	80	40	2.6	6.5	3
17	200	30	3	30	1	62	200	30	3	30	3
18	200	30	3	30	1	63	200	30	3	30	3
19	220	110	10	42.5	1	64	220	110	10	42.5	3
20	220	110	10	42.5	1	65	220	110	10	42.5	3
21	90	80	7.5	8	1	66	90	80	7.5	8	3
22	90	80	7.5	8	1	67	90	80	7.5	8	3
23	200	50	6.5	70	2†	68	200	50	6.5	70	4§
24	280	60	4.6	55	2	69	280	60	4.6	55	4
25	120	50	3	26	2	70	120	50	3	26	4
26	180	75	4	32	2	71	180	75	4	32	4
27	100	100	2.8	15	2	72	100	100	2.8	15	4
28	80	40	2.6	6.5	2	73	80	40	2.6	6.5	4
29	200	30	8	35	2	74	200	30	8	35	4
30	200	50	6.5	70	2	75	200	50	6.5	70	4
31	280	60	4.6	55	2	76	280	60	4.6	55	4
32	280	60	4.6	55	2	77	280	60	4.6	55	4
33	120	50	3	26	2	78	120	50	3	26	4
34	180	75	4	32	2	79	180	75	4	32	4
35	180	75	4	32	2	80	180	75	4	32	4
36	100	100	2.8	15	2	81	100	100	2.8	15	4
37	80	40	2.6	6.5	2	82	80	40	2.6	6.5	4
38	80	40	2.6	6.5	2	83	80	40	2.6	6.5	4
39	200	30	3	30	2	84	200	30	3	30	4
40	200	30	3	30	2	85	200	30	3	30	4
41	220	110	10	42.5	2	86	220	110	10	42.5	4
42	220	110	10	42.5	2	87	220	110	10	42.5	4
43	90	80	7.5	8	2	88	90	80	7.5	8	4
44	90	80	7.5	8	2	89	90	80	7.5	8	4
45	90	80	7.5	8	2	90	90	80	7.5	8	4

* 1 denotes the lower layout domain in the north board.
† 2 denotes the upper layout domain in the north board.
‡ 3 denotes the lower layout domain in the south board.
§ 4 denotes the upper layout domain in the south board.



(a) (b)

Figure 5: One layout example of Problem 4 (a) The layout of the north (left) board (b) The layout of the south (right) board

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