Performance Analysis of Unequal Area Facility Layout Problem when Superimposed by Load Transport and Empty Flow Networks

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***Abstract*—Given the area of the workcenters and the required loaded flow matrix between pairs of workcenters, the unequal facility layout problem (UA-FLP) is concerned with a continuous model for the arrangement of the workcenters under a loaded flow-distance objective function. In UA-FLP models, distances are measured between the centroids of the workcenters on arbitrary bidirectional free rectilinear flow paths. While these assumptions may work for gantry cranes, they are far from reality for vehicle-based material transport systems. In this study, starting from the block layouts obtained under the UA-FLP assumptions, we move towards superimposing them by material transport networks and input/output (IO) stations. We report the gaps between the objective function value under UA-FLP assumptions, that of the deterministic optimization model developed under more realistic assumptions, and that of simulation experiments to incorporate stochastic aspects.**

***Index Terms*—unequal area facility layout problem, facility planning, material handling network design, automatically guided vehicle systems**

I. Introduction

The hardest theoretical part of UA-FLP optimization models is a set of constraints to prevent the overlap of indivisible workcenters in horizontal or vertical directions. Constraints such as restricting the shape of the workcenters to rectangles, or restricting the arrangement of the workcenters to specific layout structures such as rectangular workcenters, flexible bay, or slicing structures, make the problem easier. Whereas constraints, such as restricting the aspect ratio (the longer to shorter side ratio) of the workcenters, requiring a fully packed layout (no space between the workcenters), or an overall rectangular building, make the problem even harder. Due to these difficulties, the largest optimally solved problem contains eleven workcenters [1]. Accordingly, countless heuristics have been developed for a problem later referred to as UA-FLP in the past 60 years.

More than computational complexity, UA-FLP suffers from practical applicability. In all the UA-FLP models, distances are measured between the centroids of the workcenters on arbitrary free rectilinear paths, which are also bidirectional. These assumptions may work specifically for equipment such as gantry cranes but are far from reality for vehicle-based material transport such as automated guided vehicle systems (AGVS) [2]. More importantly, the UA-FLP models' objective function minimizes the loaded segments of transports where the empty flows connecting these loaded segments are entirely ignored.

In this study, starting from a block layout obtained under the UA-FLP assumptions, we move towards superimposing UA-FLP design with input/output (IO) stations and a material transport network on contourlines defining the boundaries of the workstations. Finally, we enrich the objective function to include empty flow.

II. Literature Review

Montreuil [3] was the first to propose a modeling framework to integrate block layout with the location of IO stations, the aisle network, and the area required for the aisles. He provided eight models dealing with various facets of his integrated design. Due to the complexity of the problem, however, no solution procedure was proposed. What was later titled UA-FLP is a part of his integrated model. Though the UA-FLP part of this formulation has $2|C|(|C|-1)$ binary variables, it is NP-hard. Since the "unequal area facility layout problem" does not include the transport network and IO station design, the "block layout problem" is perhaps a more realistic title. First, "unequal area" seems redundant since an "equal area facility layout problem" practically does not exist. Second, "block layout" is more realistic than "facility layout" since "facility layout" incorporates the location of I/O stations, the material transport network, and aisle widths. Accordingly, the block layout design problem (BLDP) may be a better fit for the content of UA-FLP.

Since Montreuil [3], a trend has been towards integrating the block layout with a material flow network. Due to the complexity of the concurrent design of the two components, the design of the material flow network commonly follows that of the block layout. Goetschalckx and Palliyil [4] developed a mixed integer programming model for simultaneously determining the location of IO stations and designing a general bidirectional material transport network on the contourlines of the work centers in a UA-FLP. No computational time is reported in this study, however.

Alagoz *et al.* [5] developed a methodology to design load transport networks on flexible bay structure (FBS) layouts. In an FBS layout [6], the rectangular workcenters are aligned in parallel horizontal or vertical bays. Workcenters in the same bay have the same length in the direction perpendicular to the bays' direction. Alagoz *et al.* [5] begin with a heuristic to identify candidate horizontal and vertical routes for the network structure. An enumeration algorithm then determines the best network structure. A non-linear programming model adjusts the workcenter area and shapes to accommodate straight lines through the length or width of the layout. A genetic algorithm then located the IO station along the network.

Lin and Lin [7] identify the location of the IO stations for flexible bay structures. Kulturel-Konak [8] design flexible bay layouts and locate the stations on the boundary of the workcenters while distances are still measured rectilinearly.

Kim and Goetschalckx [10] and Friedrich *et al.* [9] sequentially design a UA-FLP integrated with a general bidirectional flow network and I/O stations. In their UA-FLP, all workcenters are rectangular but are not restricted to any other specific structure, such as flexible bay or slicing structures. Asef-Vaziri *et al.* [2] develop heuristic procedures for concurrent UA-FLP, material transport network, and IO station location design. Unlike all other studies in this review, and in general, in UA-FLP, their objective function includes both loaded and empty flow, on the contourlines, between pairs of IO stations. This measure of effectiveness is the primary determinant of the fleet size of the vehicles, which in turn is the primary driver of the total investment and operational costs in vehicle-based material handling. These three studies seem to have developed the most comprehensive models since Montreuil [2] and Goetschalckx and Palliyil [4].

III. A Test Problem

A. Armour and Buffa Benchmark Problem

Armour and Buffa [11] twenty workcenter problem (AB20) has been used more than any other benchmark to report the quality of solutions and solution times for the optimization models and heuristic procedures developed for UA-FLP. The input data include workcenters' area, the loaded transport matrix (f'_{ck}), and the unit-load cost matrix (c_{ck}).

Some load intensities and unit costs data are inconsistent in [11] and have been carried over in the subsequent papers. All the elements of the load intensities are symmetric ($f'_{ck} = f'_{kc}$), except for $f'_{13,18} = 40$ while $f'_{18,13} = 0$. We may leave them as they are since $c_{13,18} = c_{18,13} = 0$ in the cost matrix. We set $f'_{18,13} = f'_{13,18} = 40$ to have a symmetric load intensity (f'_{ck}) matrix. Some load intensities ($f'_{11,17}, f'_{17,11}, f'_{11,18}$, and $f'_{18,11}$) are strictly positive while their associated costs are zero. We leave them as they are since they will not influence $f_{ck} = c_{ck} f'_{ck}$ matrix.

In addition, all the elements of the cost matrix are symmetric ($c_{ck} = c_{kc}$) except for $c_{11,16} = 0.015$ while $c_{16,11} = 0$. We set $c_{16,11} = c_{11,16} = 0.015$ since $f'_{11,16} = f'_{16,11} = 1500$ will form a symmetric $f_{ck} = c_{ck} f'_{ck}$ matrix. Furthermore, some costs ($c_{11,19}$ and $c_{19,11}$) are strictly positive while their associated flows are zero. We leave them as they are since they will not influence $f_{ck} = c_{ck} f'_{ck}$ matrix.

In analyzing the quality of the heuristics reported in the UA-FLP literature for AB20, $f_{ck} = c_{ck} f'_{ck}$; $\forall c, k$ are considered load intensity matrix. The centroid-to-centroid distances between pairs of workcenters (d_{ck}) are the decision variables computed inside the optimization or heuristic models developed for UA-FLP. The summation of $f_{ck} d_{ck} \forall c, k$ is the loaded flow objective function to be minimized.

TABLE I
THE UNIT-LOAD TRANSPORT DATA ($f_{ck} = c_{ck} f'_{ck}$) IN AB20.

Area	27	18	27	18	18	18	9	9	9	24	60	42	18	24	27	75	64	41	27	45	600
OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	O
1		1.8	1.2							1.04	1.12			1.2							6.36
2			0.96	24.45	0.78		13.95		1.2	1.35									6.9		49.59
3						2.21			3.15	3.9				13.05					13.65		35.96
4					1.08	5.7	7.5		2.34			1.4						1.5	15.75		35.27
5							2.25	1.35		1.56					1.35						6.51
6							6.15					0.45						1.05			7.65
7								24		1.87				0.96				1.65		3.75	32.23
8													0.6						7.5	33.45	41.55
9														7.5			7.5				15.00
10											0.36	12		18.6	1.92				5.25		38.13
11												2.25		3	0.96	22.5					28.71
12															1.65		15		8.4		25.05
13														8	1.04	6					15.04
14															9.75			0.9			10.65
15																	5.25				5.25
16																	12				12.00
17																			7.5		7.50
18																			4.65		4.65
19																					0.00
20																					0.00
I	0	1.8	2.16	24.45	1.86	7.91	29.85	25.35	6.69	9.72	1.48	16.1	0.6	52.31	16.67	28.5	39.75	5.1	69.6	37.2	377.10
O	6.36	49.59	35.96	35.27	6.51	7.65	32.23	41.55	15	38.13	28.71	25.05	15.04	10.65	5.25	12	7.5	4.65	0	0	377.10

We follow the same practice and consider $f_{ck} = c_{ck} f'_{ck}$ as the elements of the load intensity matrix. Following our slight corrections in AB20 data, $f'_{ck} = f'_{kc}$ and $c_{ck} = c_{kc}$; $\forall c, k$, and therefore, $f_{ck} = f_{kc}$; $\forall c, k$. Accordingly, we only include $f_{ck} = c_{ck} f'_{ck}$; $\forall c < k$ in the modified loaded flow matrix. In the original data set, the same load volume sent from workcenter c to workcenter k is sent back to workcenter c. Our assumption does not damage the objective function values reported in the literature since they are twice what we compute. However, our assumption creates a more realistic picture in the simulation experiments. Table I shows the load intensity matrix with 62 non-zero flows; the density of the upper diagonal elements is 32.6%. The average flow in the upper diagonal is 1.98, and for the non-zeros is 6.08. The rest of the rows of Table I are explained in the simulation section.

B. Goncalves et al. *Solution*

Goncalves and Resende [12] combine (i) a biased random-key genetic algorithm to determine the order of placement and the dimensions of each workcenter, (ii) a placement strategy to position each workcenter, and (iii) a linear programming model to fine-tune the block layout design. The proposed approach is tested on random and benchmark datasets from the literature and compared with reported solutions. Their compact layout in a 30 by 20 rectangle for AB20 is shown in Figure 1.

The objective function in UA-FLP is the minimization of the sum of the flow-distances between the centroids of the pairs of the workcenters, and it is equal to 2510.59. Our objective

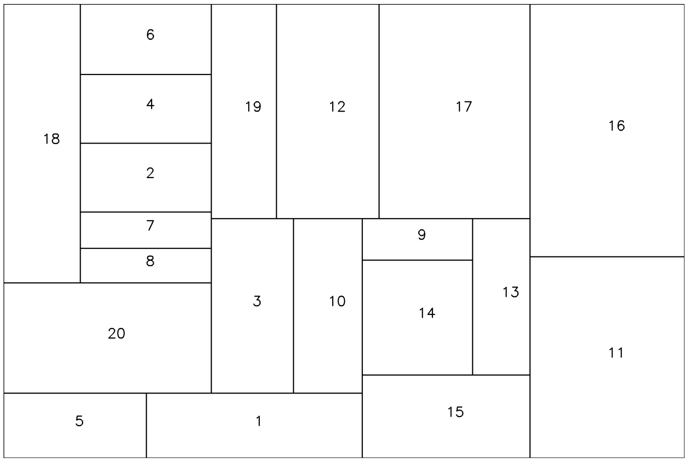

Fig. 1. The Best Solution for AB20 [12].

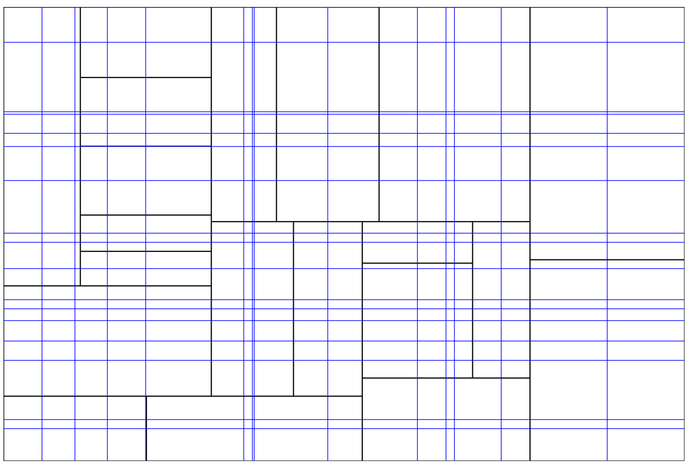

Fig. 2. The Horizontal and Vertical Aisles Superimposed on the UA-FLP Design in Figure 1.

function value for this layout is 2620.34. The 4.4% gap is mainly due to the correction we applied on AB20 data by switching $c_{16,11}f_{16,11}$ from 0 to 0.015(1500). By including this correction, their objective function value increases to 2623.09, and the gap is reduced to 0.11%. This negligible gap is because we did not have the data of their design in [12]. We scanned the layout and extracted the coordinates of interest. Given C as the set of the workcenters in a layout, as observed in Figure 2, implementing up to $2|C|$ aisles throughout the centroids of all workcenters is not practically impossible. This network may also have up to $|C|^2$ intersections, making vehicle routing and traffic management complex in real-life implementation and the simulation test-bed.

IV. A Bidirectional Network Formulation

In this section, we develop an optimization model to design a bi-directional unit-load transport network and IO stations on UA-FLP. Contourlines defining the boundaries of the workcenters are candidates to form the transport networks. The nodes where the contourlines intersect are candidates for IO station locations. Input and output stations are collocated.

In our model, we assume unit-load automatic guided vehicles (AGVs) perform load transport tasks between pairs of stations. The Worldwide AGVs market is expected to grow from about \$4 billion in 2020 to about \$9 billion in 2030. Unit-load AGVs have the largest segment in the AGV market. They are exceptionally efficient when capable of an automated interface with conveyors at I/O stations [20].

Our notations are summarized below.

A. Sets, Parameters, and Decision Variables

C: the set of workcenters in the UA-FLP.
N: the set of nodes.
A: the set of directed contourlines; two arcs per contourline.
N_c: the set of nodes on workcenter c.
A_c: the set of directed arcs on workcenter c.
B_c: the set of directed arcs connected to the boundary of workcenter c.
N_n: the set of nodes adjacent to node n.
l_{mn} the length of arc mn on contourline connecting nodes m and n.
y_{mn} = 1 if the undirected contourline $mn : m < n$ is on the network, and 0 otherwise.
P_{cn}: = 1 if node n is the IO station for workcenter c, and 0 otherwise.
t_{ckmn} = 1 if the loaded flow f_{ck} passes through the directed arc mn, and 0 otherwise. It is defined only for $f_{ck} > 0$.
T_{mn} = the intensity of empty flow on arc mn.

B. Model Formulation

Following almost all UA-FLP formulations, our first objective function (1) is to minimize the loaded transport. The key difference in our first model is to replace the centroid-to-centroid free flow with the flow between IO stations on the bidirectional network formed on the contourlines.

$$\text{Minimize } Z = \sum_{mn\in A} l_{mn} \sum_{c,k} f_{ck} t_{ckmn} \tag{1}$$

subject to

$$\sum_{n\in N_c} P_{cn} = 1 \quad \forall\, c \in C \tag{2}$$

$$\sum_{mn\in A} t_{ckmn} + P_{cn} = \sum_{mn\in A} t_{cknm} + P_{kn} \quad \forall\, f_{ck} > 0, \forall\, n \in N \tag{3}$$

$$t_{ckmn} \le y_{mn} \quad \forall\, mn \in A \tag{4}$$

$$P_{cn} \in \{0,1\} \quad \forall\, c \in C,\ \forall\, n \in N_c \tag{5}$$

$$y_{mn} \in \{0,1\} \quad \forall\, mn \in A \tag{6}$$

$$1 \ge t_{ckmn} \ge 0 \quad \forall\, f_{ck} > 0,\ \forall\, mn \in A \tag{7}$$

Constraints (2) enforce a single combined IO station for each workcenter. Constraints (3) ensure loaded flow conservation on all nodes. Constraints (4) are flow feasibility constraints stating that the vehicles can transport only through the arcs on the network. The rests are integrality and non-negativity constraints. Linear variables t_{ckmn} come out binary in the LP-relaxation.

The following constraints may also be added. Constraints (8) enforce each workcenter to have at least one contourline on the network. They provide flexibility if the workcenter cannot precisely locate its station on the intersection node. Constraints (9) will not let two adjacent workcenters collocate their stations off the network. Constraints (10) could play a role in creating a tighter LP-relaxation for Constraints (3) and (4).

$$\sum_{mn \in A_c} y_{mn} \geq 1 \quad \forall c \in C \tag{8}$$

$$\sum_{m \in N_n} (y_{mn} + y_{nm}) \geq P_{cn} \quad \forall n \in N_c \ \forall c \in C \tag{9}$$

$$\sum_{mn \in B_c} y_{mn} \geq 1 \quad \forall c \in C \tag{10}$$

The objective function (1) subject to Constraints (2)-(8) leads to 1387 unit-distance of loaded flow on the contourlines. The solution time is < 1 seconds. The objective function value is less than 2623 obtained under UA-FLP assumptions for two reasons. First, our model does not include inter-workcenter centroid-to-station distances. These distances can be computed outside the model for each workcenter and then multiplied by the incoming and outgoing loads of that workcenter. Second, the IO stations of some adjacent workcenters are collocated (1,15; 2,4,19; 8,18,20; 9,13,17; 10,14; and 11,16). A total of 129.15 loads (1/3 of all loads) are transferred stationary without needing a vehicle. A human operator, pick-and-place robot, or a short conveyor segment may handle the stationary transfers. The length of the shortest network was 45. The minimal length of the network for the optimal loaded flow was 72. The time to find the shortest network and the minimal loaded flow on the shortest network was < 1 second.

V. Empty Flow Included Objective Function

One other fundamental shortcoming of UA-FLP is minimizing the total loaded flow. The loaded flow optimal design is far from optimal when both loaded and empty flows are considered [22], [23], and [26]. We upgrade the objective function of the network and station design models to minimize the total loaded and empty flow. It is the summation of the intensity of loaded and empty flow on each contourline multiplied by the length of the contourline. This objective function is the primary determinant of the fleet size of the vehicles, which in turn is the primary driver of the total system cost.

Empty vehicle dispatching policies discussed in the literature for either design or operations of vehicle-based systems such as unit-load AGVS can be partitioned into two main classes. An empty vehicle is dispatched to the most prolonged waiting load in first-come-first-served (FCFS) dispatching and its variations [4], [27]. The FCFS dispatching in the design phase is stochastic in spirit. It attempts to approximate the dynamic behavior of the vehicle system. An empty vehicle is dispatched to the closest waiting load in shortest-trip-distance-first (STDF) dispatching and its variations [4], [28]. The STDF dispatching in the design phase is deterministic. It ignores the dynamic behavior of the vehicle system during the planning horizon. When the volume of the empty flow is integrated into the design phase's optimization model, the empty flow is a parameter under FCFS dispatching and a decision variable under STDF dispatching [24], [25]. It is experimentally shown that dictating the FCFS empty flow as input data to the optimization model leads to sub-optimization of the design and over-estimation of the vehicle fleet size [26]. Furthermore, the required load transport input to UA-FLP are the segments of loaded flow between pairs of workcenters. Such isolated pairs do not tabulate the total flow in the transformation process. By computing empty flows inside the mode, we replace these isolated flows with complete start-to-finish loaded and empty flow tours and thoroughly consider the complete transport history.

The objective function (1) is replaced by (11), where T_{mn} is the intensity of the empty trips on the directed arc mn. Constraints (12) are the flow conservation constraints for both loaded and empty flow on each node. Constraints (13) do not allow empty vehicles to travel on the arcs that are not on the network.

$$\text{Minimize } Z = \sum_{mn \in A} l_{mn} (\sum_{c,k} f_{ck} t_{ckmn} + T_{mn}) \tag{11}$$

$$\sum_{mn \in A} \sum_{c,k} f_{ck}(t_{ckmn} - t_{cknm}) = \sum_{nm \in A} (T_{nm} - T_{mn}) \quad \forall n \in N \tag{12}$$

$$T_{mn} \leq \sum_{c,k} f_{ck} y_{mn} \quad \forall mn \in A \tag{13}$$

$$T_{mn} \geq 0 \quad \forall mn \in A. \tag{14}$$

The optimal solution for the bidirectional network under the loaded and empty objective function is shown in Figure 3. The value of the objective function of minimization of the total loaded and empty flow is 1759 (about a 27% increase compared to loaded flow minimization). The solution time was < 1 second. The inter-workcenter centroid to IO station transport for this loaded and empty optimal solution is 2815. Therefore, the total inter-wiorkcenter and intra-workcenter contourline transport add up to 4574. The minimal length of the network for the optimal loaded and empty flow was 72. As computed earlier, the length of the shortest network was 45. The minimized loaded and empty flow on the shortest network was 1894 (about 8% higher than the minimal loaded flow objective function value).

VI. Simulation Experiment

In the previous sections, we developed deterministic optimization models to show the gap between the values of the objective function obtained under the assumptions of UA-FLP (or BLDP in our terminology) and what may be observed in a more realistic implementation in a deterministic world. In this section, we develop a simulation test bed to examine the gaps due to the impact of the components not embedded in the optimization model, the stochastic nature of the problem, congestion, and bocking.

Let us return to Table I to set a better stage for the simulation experiments. The numbers under column (O) represent the

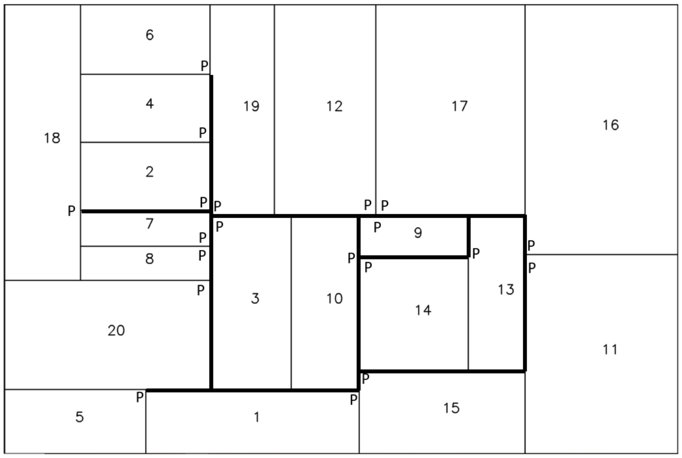

Fig. 3. The optimal bidirectional network and stations on the UA-FLP designed in [12] for AB20.

number of unit-loads sent from a workcenter in a row to all other workcenters. The numbers in row (I) represent the number of unit-loads sent from all workcenter to a workcenter in the column. We have copied column (O) under row (I).

G = O-I>0 represents unit-loads of the purchased input, parts, and components entering the manufacturing process through a workcenter. They are generated following Exponential distribution with the average of Ta = 1/G. On average, 209.34 loads are generated in all workcenters in two hours. F = I-O>0 is the number of the finished products that have left the production process after completion in a workcenter. R = I+G = O+F is the throughput of the workcenter. Rp = U $\times$ R is the capacity of the workstation, where U (utilization) is set to 75%.

For the simulation purpose, we have assumed that the building is 210 by 140 feet compared to 30 by 20 (or an aspect ratio of 3 to 2) assumed in the literate. Therefore, the objective function value for the bidirectional network designed on [12] is replaced by 7$\times$ 1759 = 12313. We have also assumed the loads will be delivered in two hours. Processing time Tp = 2/Rp and interarrival time of Ta=2/R follow Exponential distribution. Given the average speed of three feet per second for an AGV, including acceleration and deceleration times, load pickup and dropdown times, our preliminary simulation observations indicate that we will not achieve the expected throughput even with a fleet size of six vehicles.

VII. Conclusions

In this study, we showed that the design obtained under UA-FLP is distanced from what may be experienced in implementation. In a deterministic world, we showed the gap between UA-FLP optimal design and when a bidirectional flow network is superimposed. In a pseudo stochastic word, we examined the results of the deterministic models against our observations in a simulation test-bed. Studies of this type may motivate UA-FLP (or BLDP in our understanding) with IO station design and material transport network design. Our future research aims to integrate the optimization models to design the unit-load transport network on a BLDP with a heuristic procedure to improve the BLDP design and make it a better fit for the optimal network design.

Acknowledgment

Thanks are due to Hedyeh Asef-Vaziri for her valuable contribution.

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