Supplementary Material: An Efficient and Fast Local Search Based Heuristic for Reel Management in a Production Line of Oil Extraction Pipes

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1 Introduction

This document companions the manuscript entitled *An Efficient and Fast Local Search Based Heuristic for Reel Management in a Production Line of Oil Extraction*, published on Computers & Operations Research, vol. XX, no. XX, pp. XX–XX, year 202X. It contains additional material regarding:

- the instances considered in the manuscript;
- the results obtained;
- the examples presented along the manuscript;
- the ILP model considered in the *RM–ILPHeur* heuristic.

2 Instances

A set with 13 instances was considered in the manuscript. A summary of these instances can be found in Table 1.

Table 1: Summary of the instances

Instance	Folder	C1	C2	C3
A	InstanceA	15	1,546	36
B	InstanceB	16	1,480	38
C	InstanceC	15	3,485	39
D	InstanceD	17	3,438	40
E	InstanceE	15	1,638	42
F	InstanceF	16	2,835	40
G	InstanceG	15	2,200	37
H	InstanceH	22	1,125	40
I	InstanceI	17	1,334	40
J	InstanceJ	24	1,913	40
K	InstanceK	26	1,206	40
L	InstanceL	21	1,862	42
M	InstanceM	20	2,328	42

in which:
C1 is the number of tasks;
C2 is the finish time of the plan (in t.u.);
C3 is the number of reels in the facility.

These instances can be found in the zip file that must be downloaded from the following GitHub page:

`https://github.com/egcarrano/COR2021a`

The zip contains 13 folders, one for each instance (see column folder in Table 1). Each instance is composed of four files:

1_vertices.csv : file containing information regarding the positions. It is composed of a single column:

POSITION : ID of the position.

2_arcs.csv : file containing information regarding the connections (arcs) between the positions. It is composed of three columns:

FROM_POSITION : ID of the start position of the arc.

TO_POSITION : ID of the finish position of the arc.

CRANE : movement unit (M.U.) that connects FROM_POSITION to TO_POSITION:

- Crane A is identified as 2.
- Crane B is identified as 1.
- CAR2 is identified as 3.

3_initial_positions.csv : file containing information regarding the initial positions of the reels. It is composed of two columns:

REEL : ID of the reel.

POSITION : position in which the reel is initially placed.

4_planning.csv : file containing information regarding the production plan to be accomplished. It is composed of seven columns:

TASK_ID : ID of the task.

START : desired start time of task processing.

FINISH : defined finish time of task processing.

REEL1 : reel associated to the sub-task 1.

REEL2 : reel associated to the sub-task 2.

POSITION1 : target position associated to the sub-task 1.

POSITION2 : target position associated to the sub-task 2.

Some features, which are common to all instances, must be considered:

Car features :

- Position 24 identifies CAR1.
- Position 25 identifies CAR2.
- The movement of CAR1 between the two sides of the facility must be modeled by the user. In our cause, we created two positions $24a$ and $24b$, which are connected as follows:
  - $24a$ is connected to 12 through Crane A.
  - $24b$ is connected to 38 through Crane B.
  - $24a$ is connected to $24b$ through a new M.U. (identified as 4). The time spent by M.U. 4 is the time required by CAR1 for moving between Side A and Side B.

  It is also necessary to ensure that positions $24a$ and $24b$ are not used at the same time.

M.U. displacement times :

- CAR1: 5 t.u.
- CAR2: 3 t.u.
- Crane A: 3 t.u.
- Crane B: 3 t.u.

Special positions : moves from and to positions 22 and 23 require special conditions to be performed:

- The moves $22 \to 16$ and $16 \to 22$ can only be performed if the position 17 is empty.
- The moves $22 \to 17$ and $17 \to 22$ can only be performed if the position 16 is empty.
- The moves $23 \to 13$ and $13 \to 23$ can only be performed if the position 14 is empty.
- The moves $23 \to 14$ and $14 \to 23$ can only be performed if the position 13 is empty.

3 Results

The results obtained by the *RM–LSHeur* method are also provided jointly with the instances. These results are given in a single CSV file:

MoveList.csv : file containing information regarding the operations, moves, and sub-moves performed to complete the plan. Each line represents a sub-move. It is composed of 11 columns:

- **TASK** : ID of the task whose the sub-move is assigned to (-1 if the sub-move is not assigned to any task).
- **SUBTASK** : ID of the sub-task whose the sub-move is assigned to (-1 if the sub-move is not assigned to any sub-task).
- **OPERATION** : ID of the operation that contains the sub-move.
- **MOVE** : ID of the move that contains the sub-move.
- **SUBMOVE** : ID of the sub-move.
- **REEL** : ID of the reel involved in the sub-move.
- **FROM_POSITION** : ID of the start position of the reel involved in the sub-move.
- **TO_POSITION** : ID of the finish position of the reel involved in the sub-move.
- **START_TIME** : start time of the sub-move.
- **FINISH_TIME** : finish time of the sub-move.
- **CRANE** : M.U. involved in the sub-move.

A summary of these results is provided in Table 2.

Table 2: Best results achieved by the proposed heuristic.

Instance	F_1	F_2	F_3	F_4	F_5
A	0	0	39	398	50
B	0	0	18	538	58
C	0	0	17	940	66
D	0	0	116	120	88
E	0	0	33	2,154	79
F	0	0	18	3,827	108
G	0	0	36	2,589	76
H	0	0	92	1,932	64
I	0	0	36	990	43
J	0	0	139	27	64
K	0	0	145	57	64
L	0	0	75	0	47
M	0	0	20	15	36

In the specific cases of instances **I**, **L**, and **M**, there is also a file **MoveListILP.csv**, which contains the final solutions achieved by the variant **RM–ILPHeur+FLSN+ELSN** of the ILP based heuristics. This file has the same structure of **MoveList.csv**, described above. The performance of such solutions is summarized at Table 3.

Table 3: Best results achieved by the **ILPHeur+FLSO+ELSN** variant.

Instance	F_1	F_2	F_3	F_4	F_5
I	0	0	36	987	44
L	0	0	74	1	46
M	0	0	142	15	34

4 Video Animation of the Examples

Video animations of examples 2 to 6 can be found through the following URLs:

Example 2 : `https://youtu.be/mAndp7v8Cqk`

Example 3 : `https://youtu.be/VpHo4Cc97-M`

Example 4 : `https://youtu.be/hI-udcfkbiE`

Examples 5 and 6 : `https://youtu.be/Q4FHhtq_BaQ`

5 ILP Model

The ILP model proposed to solve each move sub-task individually inside *RM–ILPHeur* is presented along this section. It has 13 groups of parameters:

- $c_{i,j,k}$ assumes 1 if M.U. k connects position i to j, or 0 otherwise.
- $p_{i,b}$ assumes 1 if reel b is initially placed at position i, or 0 otherwise.
- t_i indicates the sub-task start time.
- t_f indicates the sub-task finish time, when reel processing ends.
- $\mathcal{Q}$ is the set of move stages. Each move stage can contain up to one sub-move of each M.U..
- $\mathcal{P}$ is the set of positions in the facility.
- $\mathcal{B}$ is the set of reels in the factory.
- $\mathcal{K}$ is the set of M.U.'s.
- $\mathcal{K}_{crane}$ is the set of cranes.
- $\mathcal{K}_{car}$ is the set of cars.
- t_{crane} is the time required for a crane move.
- t_{car} is the time required for a car move.
- w_{mov} is a constant that weights the relationship between earliness time and sub-moves.

In addition, the model has three sets of decision variables:

- $pos_{i,b,q}$ is a binary variable that assumes 1 if the position i is occupied by the reel b at move stage q, or 0 otherwise.
- $mov_{b,i,j,k,q}$ is a binary variable that assumes 1 if there is a sub-move of reel b, from position i to j, using the M.U. k, at move stage q, or 0 otherwise.
- t_q is a variable that represents the time until the move stage q.

The constraints are represented from Equation 1 to Equation 15.

$$pos_{i,b,q} - pos_{i,b,q+1} = \sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{P}} mov_{b,i,j,k,q+1} - \sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{P}} mov_{b,j,i,k,q+1} \quad \forall\ q\in\mathcal{Q}, b\in\mathcal{B}, i\in\mathcal{P} \tag{1}$$

$$\sum_{i\in\mathcal{P}} pos_{i,b,q} = 1 \quad \forall\ q\in\mathcal{Q}, b\in\mathcal{B} \tag{2}$$

$$\sum_{b \in \mathcal{B}} pos_{i,b,q} \leq 1 \quad \forall\ q \in \mathcal{Q}, i \in \mathcal{P} \tag{3}$$

$$mov_{b,i,j,k,q} \leq c_{i,j,k} \quad \forall\ q \in \mathcal{Q}, b \in \mathcal{B}, k \in \mathcal{K}, i \in \mathcal{P}, j \in \mathcal{P} \tag{4}$$

$$\sum_{b \in \mathcal{B}} \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} mov_{b,i,j,k,q} \leq 1 \quad \forall\ q \in \mathcal{Q}, k \in \mathcal{K} \tag{5}$$

$$\begin{aligned} &\sum_{b \in \mathcal{B}} mov_{b,12,24a,2,q} + \sum_{b \in \mathcal{B}} mov_{b,24a,12,2,q} + \\ &\sum_{b \in \mathcal{B}} mov_{b,24a,24b,4,q} + \sum_{b \in \mathcal{B}} mov_{b,24b,24a,4,q} + \\ &\sum_{b \in \mathcal{B}} mov_{b,24b,38,1,q} + \sum_{b \in \mathcal{B}} mov_{b,38,24b,1,q} \ \leq 1 \quad \forall\ q \in \mathcal{Q} \end{aligned} \tag{6}$$

$$\begin{gathered} \sum_{b \in \mathcal{B}} \sum_{i \in \mathcal{P}} mov_{b,i,25,3,q} + \\ \sum_{b \in \mathcal{B}} \sum_{i \in \mathcal{P}} mov_{b,i,25,1,q} + \sum_{b \in \mathcal{B}} \sum_{i \in \mathcal{P}} mov_{b,25,i,1,q} \ \leq 1 \quad \forall\ q \in \mathcal{Q} \end{gathered} \tag{7}$$

$$\sum_{b \in \mathcal{B}} pos_{24a,b,q} + \sum_{b \in \mathcal{B}} pos_{24b,b,q} \ \leq 1 \quad \forall\ q \in \mathcal{Q} \tag{8}$$

$$pos_{i,b,1} = p_{i,b} \quad \forall\ b \in \mathcal{B}, i \in \mathcal{P} \tag{9}$$

$$\begin{aligned} t_1 = t_i + \max \Bigg[&\min \left(t_{crane}, \sum_{k \in \mathcal{K}_{crane}} \sum_{b \in \mathcal{B}} \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} t_{crane} \cdot mov_{b,i,j,k,1} \right), \\ &\min \left(t_{car}, \sum_{k \in \mathcal{K}_{car}} \sum_{b \in \mathcal{B}} \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} t_{car} \cdot mov_{b,i,j,k,1} \right) \Bigg] \end{aligned} \tag{10}$$

$$\begin{aligned} &t_q = t_{q-1} + \\ &\max \Bigg\{ \min \left[t_{crane}, \sum_{k \in \mathcal{K}_{crane}} \sum_{b \in \mathcal{B}} t_{crane} \cdot \max \left(0, \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} mov_{b,i,j,k,q} - \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} mov_{b,i,j,k,q-1} \right) \right], \\ &\min \left[t_{car}, \sum_{k \in \mathcal{K}_{car}} \sum_{b \in \mathcal{B}} t_{car} \cdot \max \left(0, \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} mov_{b,i,j,k,q} - \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} mov_{b,i,j,k,q-1} \right) \right] \Bigg\} \ \forall\ q \in \mathcal{Q} \end{aligned} \tag{11}$$

$$\sum_{q \in \mathcal{Q}} \sum_{b \in \mathcal{B}} pos_{16,b,q} + mov_{b,17,22,2,q+1} + mov_{b,22,17,2,q+1} \ \leq 1 \tag{12}$$

$$\sum_{q \in \mathcal{Q}} \sum_{b \in \mathcal{B}} pos_{17,b,q} + mov_{b,16,22,2,q+1} + mov_{b,22,16,2,q+1} \ \leq 1 \tag{13}$$

$$\sum_{q \in \mathcal{Q}} \sum_{b \in \mathcal{B}} pos_{13,b,q} + mov_{b,14,23,2,q+1} + mov_{b,23,14,2,q+1} \ \leq 1 \tag{14}$$

$$\sum_{q \in \mathcal{Q}} \sum_{b \in \mathcal{B}} pos_{14,b,q} + mov_{b,13,23,2,q+1} + mov_{b,23,13,2,q+1} \ \leq 1 \tag{15}$$

Equation 1 represents a set of flow constraints, i.e. if a position receives or provides a reel, it should have a corresponding sub-move. Constraints (2) and (3) ensure that a reel must be in one position at a time and that each position cannot store more than one reel at a time, respectively.

Equation 4 defines that a sub-move is possible only if there is a valid path between the corresponding positions. Constraints (5) ensure that a given M.U. cannot be demanded more than one time at a given move stage.

Constraint (6) states that CAR1 cannot execute more than one of the following activities at a given move stage: *i*) receive a reel from Side A; *ii*) deliver a reel to Side A; *iii*) move a reel from Side A to Side B; *iv*) move a reel from Side B to Side A; *v*) deliver a reel to Side B, or; *vi*) receive a reel from Side B. Constraint (7) defines similar conditions to CAR2 (however considering that it is only connected to Side B). Since CAR1 is modeled as two individual positions, $24a$ and $24b$, constraint (8) defines that the two positions cannot be used simultaneously.

Constraint (9) defines the initial distribution of the reels along the facility positions. Equation 10 updates the planning time for the first move stage, taking into account the initial time, which is a model input. Since M.U.'s can be operated simultaneously, if two or more M.U. are active at the same move stage, the finish time of the movement becomes the maximum among M.U. finish times. Constraints (11) update the planning time for the remaining move stages. This equation is different from the previous one because sequential sub-moves performed by the same reel, without interruptions, are grouped into a same move, with the same execution time interval.

Finally, equations (12) to (15) implement the constraints related to moves $23 \rightarrow 13$, $13 \rightarrow 23$, $23 \rightarrow 14$, $14 \rightarrow 23$, $22 \rightarrow 16$, $16 \rightarrow 22$, $22 \rightarrow 17$, and $17 \rightarrow 22$.

The objective function considered in the proposed model is shown in Equation 16. Given the sub-task reel and position, it aims to maximize the earliness and minimize the number of sub-moves, through a weighted sum of the objectives.

$$\max \sum_{q \in \mathcal{Q}} \max\left(0, t_f \cdot pos_{p,b,q} - t_q\right) - w_{mov} \cdot \sum_{q \in \mathcal{Q}} \sum_{k \in \mathcal{K}} \sum_{b \in \mathcal{B}} \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} mov_{b,i,j,k,q} \tag{16}$$

Some features of this model deserve some discussion:

- The use of earliness as the objective function is justified by the fact that it is not possible to explicitly represent tardiness, since the two sub-tasks associated to a given task are handled separately. Therefore, earliness is employed as a proxy function for tardiness.

- The purpose of representing the number of sub-moves in the objective function is to avoid the construction of unnecessarily lengthy moves. The parameter w_{mov} should be set in such a way that the first term of the sum has priority over the second one.

- The concept of operation is not defined in this model, which means that F_2 and F_5 are not explicitly handled.