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► **To cite this version:**

Damien Lovato, Romain Guillaume, Caroline Thierry, Olga Battaïa. Aircraft final assembly line planning with staircase makespan and equity criteria. 10th IFAC Conference on manufacturing modelling, management and control (MIM 2022), IMT Atlantique; IFAC: International Federation of Automatic Control, Jun 2022, Nantes, France. à paraître. hal-03792964

HAL Id: hal-03792964

<https://hal.science/hal-03792964v1>

Submitted on 30 Sep 2022

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Aircraft final assembly line planning with staircase makespan and equity criteria

D. Lovato*, R. Guillaume*, C. Thierry*, O. Battaïa**

* Univ. Toulouse, IRIT, 31400 Toulouse, France
(e-mails: {damien.lovato, caroline.thierry}@univ-tlse2.fr, romain.guillaume@irit.fr).

** KEDGE Business School, 33405 Talence, France
(e-mail: olga.battaia@kedgebs.com)

Abstract: The ergonomic aspect in the assembly lines has become very important to consider nowadays. Its study helps improving operator's environment and life quality at work. This ergonomic study in aircraft assembly lines showed that some tasks increase the risks of musculoskeletal disorders. In order to help industrial managers to reduce these risks, a novel ergonomic index for task scheduling has been developed. This index has the objective of improving the solution quality in terms of ergonomic fairness by balancing difficult tasks between each operator. This criterion has been used in a model that has then been tested on real-life instances of aircraft assembly line to witness its efficiency.

Keywords: Aircraft Final Assembly Line, Scheduling, Ergonomics, RULA, fairness.

1. INTRODUCTION

An aircraft Final Assembly Line (FAL) consists of a series of assembly stations where tasks are being processed. There is a predefined limited time available for the realization of the tasks assigned to each assembly station, called takt time or Production Interval (PI). When the takt time is over, every aircraft advances to the next assembly station for a new series of tasks. To be completed, every aircraft has to go through all assembly stations.

The work in FAL is highly manual and some hard tasks can impact the health of operators, for example, those requiring a prolonged uncomfortable position as shown in Figure 1.

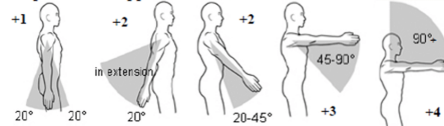


Figure 1 - Importance of ergonomics

Several ergonomic methods can be used for the evaluation of hardness and strain of the tasks, for example, the Rapid Upper Limb Assessment (RULA) index, which evaluates how upper body is affected by tasks. This index takes into account different ergonomic parameters (see Figure 2) in order to evaluate how uncomfortable the working position is.

A. Arm and Wrist Analysis

Step 1: Locate Upper Arm Position:



Step 1a: Adjust...

If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

Step 2: Locate Lower Arm Position:



Step 2a: Adjust...

If either arm is working across midline or out to side of body: Add +1

Lower Arm Score

Step 3: Locate Wrist Position:



Figure 2 - Example of RULA evaluation for arm and wrist

Source: https://www.researchgate.net/figure/RULA-employee-assessment-worksheet-16_fig1_326232801

In practice, such an evaluation is usually made when the tasks are already assigned to assembly stations and operators. Such a posteriori evaluation cannot prevent from an unfair task distribution where some operators have to manage a bigger number of hard tasks than any of their colleagues.

In order to provide managers with efficient scheduling tools that take into account the ergonomic impacts of task assignment, we develop in this paper a new mathematical model that can be solved with constraint programming approach.

Our objective is to provide managers with a procedure capable to evaluate the fairness of tasks distribution among operators and propose the fairest solution. A better equity reduces the

risks of accidents and favors group's unity since no operator will envy an easier schedule from another one.

In order to better understand the considered context, a state of the art on the ergonomic approaches and equity is presented in Section 2. Section 3 is dedicated to the presentation of our Constraint Programming (CP) model with its related criteria. This model is tested on industrial instances in Section 4. Finally, conclusions and future research directions are discussed in Section 5.

2. STATE OF THE ART

This section presents briefly some equity tools and ergonomic indexes to give a general perception on how the concept of equity has been used in the ergonomic field.

An equivalent sharing and division of goods always has been an important aspect in the human culture. This also has always been a very complex topic because of the differences in personal appreciations of values of goods. This means that an equal division from a mathematic point of view may not be the best solution. When the preferences of participants can be expressed, then the division method needs to take them into account.

The Competitive Equilibrium from Equal Incomes (CEEI) method has been formalized by Walras (1874) and Fisher (1892). CEEI relies on the fact that people from a group have an equal income (fictive) and may buy goods from what has to be divided. The objective is that they have the goods they desire to maximize their satisfaction, and no one envies another one from the group, subject to their limited income. A method based on this concept has been elaborated by Budish (2011) who revised it to share non-divisible objects between people.

These equity concepts have also introduced inequality indexes that measure the inequality of an allocation (of a resource, or tasks in our case). The Gini index, developed by Corrado Gini, is one of them. When used in economics, its objective is to measure statistical dispersion, representing income or wealth inequality between populations or groups of different size. Gini index is defined mathematically on Lorenz curve. More information on Gini index and Lorenz curve can be found in the book of Moulin (1988) in chapter 2.

As mentioned earlier, several ergonomic methods exist for measuring the ergonomic demand of an action, or a task. While the RULA seems to be the most used nowadays, Kee (2021) compares it with two other methods (OWAS and REBA) to evaluate musculoskeletal disorders on different industrial sites' data. Joshi and Deshpande (2021) conducted a deep analysis on how each factor (arms position, trunk, legs) affects the score given by the RULA index. They identified the arms position as the most influencing factor. The RULA index has been used by Wilhelm et al. (2021) with their indicator ErgoTakt to capture and evaluate the ergonomic on their assembly line in real time. Boenzi et al. (2016) uses the Occupational Repetitive Action (OCRA) index in an industrial case to lighten the ergonomic charge on a specific subgroup of workers. This index evaluates risks for repetitive handling at high frequency. The associated algorithm

evaluates every different job rotation to select the most suited one.

In comparison, Mokhtarzadeh et al. (2021) use multiple indexes. They developed a two-stages framework to balance a mixed model U-shaped assembly line. In the first part they evaluate the tasks' difficulty using various indexes: OCRA, JSI, NIOSH, EAWS, OWAS and COPSOQ. Their objective is to get a more accurate notation for tasks in association with methods like ELECTRE TRI which aims at assigning items to classes based on a number of criteria. In a secondary part, a mathematical model is built to assign the tasks to each workstation, which made their framework quite complete and adapted to both big-size and small-size problems.

Katirae et al. (2021) created their own matrix including individual characteristics and perceptions of workers for every task based on their experience and physical efforts. To help these workers to evaluate these tasks, they use the Borg scale, introduced by Borg (1990) and a bi-objective model to solve a small-size instance.

Arkhipov et al. (2018) worked on a two-part solver to take into account ergonomics in a low-volume assembly line with long cycle times. Their solver uses both a CP and an ILP model and has been tested on two industrial instances.

Based on the nature of the work on the assembly line, the most suitable index for measuring risks is the RULA, since tasks are mostly upper-body demanding. Thanks to this method, we consider that every task is already evaluated and has an ergonomic score. Then, while most of the papers use the index itself to classify tasks, we chose to also use the task duration to normalize the difficulty per time unit for each one of them. The other paper that wanted to go further than one index has used several but didn't consider the specificities of tasks like this duration and this is what we are aiming at in this paper. We thus present in the next section the CP model that is used along with its criteria and some main constraints.

3. INTEGRATION OF ERGONOMIC CRITERION IN CP MODEL

The scheduling problem has as objective to assign the known tasks to operators. This assignment has to respect a number of constraints: precedence one between tasks, zone constraints for tasks performed at the same time, the skill adequation constraints requiring the skill mastered by the operator and the one necessary to execute the task to match. In the following, we present this model in detail.

3.1. Input parameters and decision variables

I represents the set of tasks i .

For every task:

- d_i is the difficulty for task i to be realized;
- pt_i the task's duration;
- r_i its RULA score which represents the load that the operator's body will have to endure.

H is the set of operators h (equivalent to human resources).

Associated to both these human resources and tasks, a set of skills S is defined, and we define:

- s_i the necessary skill to realize task i ;
- s_h the skill mastered by operator h (each operator only master one skill during the whole scheduling).

For each skill, the subset H_s defines the set of operators mastering skill s . Thus:

- $\bigcup_{s \in S} H_s = S$
- $\bigcap_{s \in S} H_s = \emptyset$

Those data represent the main information's needed to express the ergonomic criterion in the Constraint Programming model.

Along with these, there are two decision variable in our CP model:

$$interval_i$$

This interval represents the interval of time when task i is being processed. It is represented by starting date, end date and duration p_i .

$$x_{i,h}$$

$x_{i,h}$ is the decision variable that equals 1 when operator h is affected to task i in the schedule, 0 otherwise.

3.2. CP Model presentation

The considered scheduling problem aims to assign tasks to operators in an aircraft FAL. The objective of the CP model isn't to find the best makespan, but to find a scheduling whose makespan matches the end of the PI. Having a makespan inferior to the PI's end would result in loss of potential time and thus inefficient work repartition. This particular makespan version has been called the "staircase makespan". Considering that the PI is divided into several days, the staircase makespan will always match the end of a day, which gives a staircase form to this objective function, as shown in Figure 3.

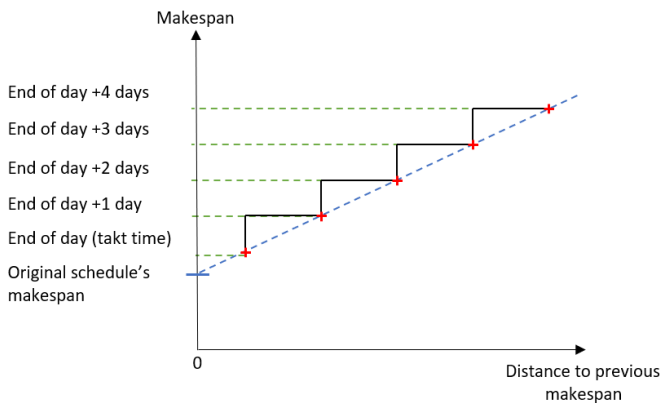


Figure 3 - Representation of the staircase makespan values evolution

Let m be a positive integer decision variable and t be the representation of a day in the temporal unity used for scheduling, the staircase makespan can be calculated by minimizing m along with the following constraint:

$$makespan \leq m * t$$

The use of this criterion saves calculation time that can be used to optimize other criteria. Every following constraint is defined thanks to functions from the OPL library in IBM ILOG CPLEX Studio. To lighten the paper, we won't enter in detail for most of them. For a more detailed description of the model with mathematical definitions and rescheduling aspect, reader can refer to our previous work (Lovato et al, 2022) where the complete model has been introduced.

- Precedence relations have to be respected between tasks. Considering two tasks i and j , they may have five expressions: i ends before j starts; j starts exactly when i ends; i must ends before j ends; i must starts before j starts; i must starts simultaneously with j .
- Limited renewable resources (both human and material) can't be exceeded during the whole scheduling. This means that at any moment, the number of involved operators or material resources cannot exceed the total available quantity for this assembly station.
- Some tasks need to be completed by the right number of operators. This value can be a single one, or several. Every material resource required for the task execution must also be available during task duration.
- The assignment of tasks must respect the working calendar associated with the operator(s) assigned to it. This calendar defines the working hours of each operator and is defined by a function whose value is 100 when operator is active and 0 when inactive. It is represented by "Calendar_o".

$$forbidStart(x_{i,h}, Calendar_h), \forall i \in I, \forall h \in H$$

$$forbidEnd(x_{i,h}, Calendar_h), \forall i \in I, \forall h \in H$$

These two constraints restraint the start and end of any task realized by operator h . They forbid any task to start or end on an interval where the assigned operator doesn't work, resulting in a paused in the occurring task. Note that the operator must finish the actual task before working on a new one.

- The assignment of operators must respect the task's demanded skill in order to be properly realized.
- In order to prevent quality problems, the aircraft is divided into working areas in such a way that only one task can be processed in each are at the same time. If an area is occupied by a task, no task can be performed in this working area until the area becomes available again. An area may also be forbidden, even if no task is being done in this area, because of another task that requires a security perimeter. Areas

may then be forbidden by several tasks. Every area is represented by a state function whose value is 1 when the area is being used by a task and 0 when the area is free.

3.3. Ergonomic criteria

We consider two ergonomic criteria based on each operator's ergonomic score and depending on the tasks' difficulty calculated with RULA evaluation. The choice of not considering the RULA score as the proxy for the task's difficulty is due to the fact that it is hard to differentiate which is harder between a task of difficulty 8 that lasts ten minutes and a task of difficulty 6 that lasts fifteen minutes. Taking this into account, for a given task $i \in I$, its respective difficulty is:

$$d_i = pt_i * \left(\frac{r_i}{100}\right)^2$$

Thus, with criterion $x_{i,h}$ that equals 1 when task i is assigned to operator h and 0 otherwise, the ergonomic load endured by an operator $h \in H$ is calculated with e_h :

$$e_h = \sum_{i \in I} x_{i,h} * d_i$$

This leads to the first ergonomic criterion that will be represented by the maximum ergonomic load amongst all operators for each different skill:

$$SUM_Max = \sum_{s \in S} \max_{h \in H_s} e_h \quad (1)$$

This first criterion is called "SUM_Max".

The second criterion has been inspired by Gini index. The difference from its classic form lies in the fact that no groups will be compared but only individuals, which requires a slight adaptation of the criterion. The denominator has been changed for the criterion to take its values between 0 and 1, and the numerator to compare only the operators mastering the same skill. This criterion is named Mean Difference Index (MDI):

$$MDI = \frac{\sum_{s \in S} \sum_{h, h' \in H_s} |e_h - e_{h'}|}{2 * (|H| - 1) * \sum_{i \in I} d_i} \quad (2)$$

where $|H|$ represents the total number of operators.

If every operator h has an exactly equal ergonomic load e_h , the MDI value is 0, which represents the perfect equality. On the opposite, in the theoretical case where every task is assigned to one operator (perfect inequality), the MDI value is 1.

Both these criteria are to be minimized by the objective function in addition to staircase makespan, considering the constraints of the problem presented here above. In order to analyze the behavior of these criteria, a computational experiment has been designed and realized. Its results are presented in the next section.

4. COMPUTATIONAL EXPERIMENTS

All tests have been run under IBM ILOG CPLEX Optimization Studio environment version 12.10 with CP

Optimizer (CPO) library incorporated. The processor used was an Intel(R) Core (TM) i7-8665U CPU @ 1.90GHz 2.11 GHz besides 16Go of memory.

4.1. Objectives

The experiments aim to evaluate:

- How both criteria may influence the schedule?
- How could they be added in a schedule calculation?
- Which criterion is better suited and for which parameters?

To study these questions, a small size industrial instance has been used. For it, the first schedule is calculated within an hour as a time limit. Thus, additional tests are realized in order to tune the analysis.

4.2. Instance details

We consider a test instance with a single aircraft being assembled, with 10 operators (6 mastering skill S1, 4 mastering skill S2), 200 different areas defined on the whole aircraft. There are 265 tasks and 3 different material disjunctive resources R1, R2 and R3 and 518 precedence constraints.

4.3 Criteria evolution

Solutions have been generated through a warm start procedure: a first run is realized to obtain the best possible value for the staircase makespan. Then, the solution is saved as a starting point and a constraint is added to not go beyond this day's end, and the objective is changed for one of the ergonomic criteria (1) or (2).

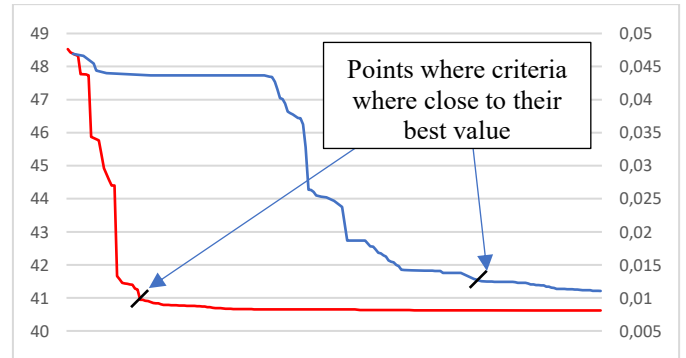


Figure 4 - Criteria evolution. Blue = MDI (2); Red = SUM_Max (1). MDI axis on right, SUM_Max axis on left.

The first observation that we make concerns the criterion's efficiency to find the best solution. Figure 4 shows each criterion evolution through time. Time axis (x-axis) has been cut off for better readability. Values on the left y-axis are the SUM_Max values (red curve) while the ones on the right y-axis are values for de MDI (blue curve). The time limit was one hour but Figure 4 only represents the first 300 seconds for better readability even though the calculation time for both criteria reached this stopping criterion.

SUM_Max is faster to reduce the gap with its optimal value than MDI. When it flattens, SUM_Max's improvements are

very low and pretty close to the optimal value (less than 2% proximity). It reached its nearly best value in 20 seconds, while it took 150 seconds for MDI to slow down its progression significantly, and 250 seconds to reach a gap to its optimal value which at least as good as SUM_Max in 20 seconds. In comparison, SUM_Max is faster in convergence than MDI.

Over the whole run, SUM_Max reduced its value by 16.3% (from 48.5273 to 40.6176) while MDI by 76,8% (from 0.0469 to 0.0109). While SUM_Max seems to be faster, MDI looks to have a better potential of improvement through time.

The SUM_Max seems to be a better suited criterion to rapidly find a good solution. This difference could be exploited by a solver. At the first step, the SUM_Max could be used to rapidly reach an advanced point for MDI to take the solution as a starting point and improve it more efficiently than SUM_Max that slows down harshly. This two-step resolution could help to find a better solution within the same computational time.

4.4. Swapping milestone

We conduct the following test for two-step optimization. First, SUM_Max is optimized until it reaches a gap to its optimal value under 2% (gap calculated by solver). Then, we take the current solution and feed it to the next step where the MDI criterion is optimized.

Table 1 shows the gap to optimum obtained for SUM_Max criterion and computational time.

Best value	Time elapsed (seconds)	Gap with optimum
44.06	16.08	8.66 %
43.69	25.29	7.89 %
40.94	43.11	1.71 %
40.87	49.36	1.54 %
40.82	53.74	1.41 %

Table 1 – Evolution of the gap for SUM_Max through time

In the following experiment, we compare the values of SUM_Max and MDI criteria when only SUM_Max is optimized vs two-step optimization where first SUM_Max is optimized then MDI. The computing time limit for each solution was of one hour.

	SUM_MAX	SUM_MAX + MDI
MDI	4.3247 E ⁻⁵	1.4194 E ⁻⁵
OP 1	36.9052	36.9018
OP 2	36.9039	36.9023
OP 3	36.905	36.9019
OP 4	36.9006	36.9024
OP 5	36.8968	36.9021

OP 6	36.9035	36.9028
OP 7	3.3856	3.3831
OP 8	3.384	3.3825
OP 9	3.3818	3.388
OP 10	3.381	3.3828

Table 2 - Ergonomic scores for operators after one hour of computing

Table 2 presents ergonomic scores for each operator obtained by two approaches: optimization of SUM_Max and two-step optimization. Operators 1 to 6 are from the same subgroup, and operators 7 to 10 from another. The MDI value also has been depicted in both cases for a better comparison.

First observation is that the MDI is three times better for two-step optimization, however, the difference between two solutions are relatively low. From an industrial point of view, these little differences can be negligible in application. Taking into account this conclusion, the use of MDI may require substantially larger computational time especially for larger groups of operators. The use of SUM_Max seems to be more appropriate for this scheduling context.

In conclusion for this part, these tests allow us to answer our initial questions:

- How both criteria may influence the schedule?

On one hand, both criteria slow the calculation of a schedule, but MDI criterion needs a bigger amount of time to get a decent solution. On the other hand, they both tend to get equal ergonomic scores amongst operators, which was the main objective.

- How could they be added in a schedule calculation?

The best addition would be when a first schedule has been fixed to have a more constrained problem and reduce the solution environment to be explored. This would gain time while calculating a better ergonomic solution while maintaining a certain degree of liberty.

- Which criterion is better suited and for which parameters?

From the results, the best criterion seems to be SUM_Max if the rapidity is the main concern when computing a solution. But if the ergonomic quality has to be as good as possible, then the MDI criterion is better suited.

5. CONCLUSIONS

In this study, we consider the context of an aircraft FAL where ergonomic conditions need to be improved. The Mean Difference Index criterion, based on the Gini index, has been developed in order to balance the ergonomic burden among the operators. The ergonomic properties of the tasks are considered to be measured by RULA method. The objective of MDI criterion is to find such an assignment of tasks to operators that the ergonomic charge is equivalent for everyone

in the group, by measuring the difference of ergonomic load between each operator from the same skill group. This criterion has been tested on a real-life instance and its efficiency has been compared with a classic minimization of the maximum value of ergonomic charge amongst all operators from the same group.

Results from tests have shown that MDI is slower at converging towards its optimal solution, but that its optimal solution looks to be better with long computing time allowed. This observation has led to a two-step optimization with in a first part, optimizing through the minimization of the maximum ergonomic charge to reach a good solution rapidly and then switching to the MDI criterion for improving the solution. However, the time required for reaching the optimal value seems to be long in the context of the industrial application and the use of SUM_Max seems to be sufficient in order to prevent the prolonged ergonomic burden.

Considering these observations, this CP Model is a good solution to rapidly get a schedule that respects ergonomic constraints. It could avoid musculoskeletal disorders to operators because in comparison with other models, it takes the RULA evaluation as a complementary metric to evaluate tasks hardness instead of completely relying on it. Therefore, our model is an interesting alternative to get a good quality solution in a NP-HARD case like this specific RCPSP problem.

In future research, we are planning to validate these results through the interviews with workers about their perception of the ergonomic strain in order to study how the psychological perception of working tasks influence the musculoskeletal disorders.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGMENT

This work has been funded by ANR Project Per4mance ANR-18-CE10-0007. We are thankful to our industrial partner Dassault Aviation for their collaboration within this project.

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