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Energy expenditure and makespan multi-objective optimization for cobots systems design

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Abstract

Nowadays, we are living a transitional period from Industry 4.0, with its principles of high productivity and high flexibility of modern production systems due to the mass customization, to Industry 5.0, that aims to realize a more human-centered design of the workplace in order to improve the operators' wellness. For this purpose, new technologies such as collaborative robots are always more integrated since they are able to guarantee, at the same time, productivity and flexibility but they can also perform the more burdensome tasks, leaving to the operators the more challenging ones. However, since these systems are thought to work directly with human operators, it is fundamental to consider the human-robot collaboration, in order to correctly assign the tasks to the resources. This is the cornerstone of Industry 5.0, that points toward the realization of human-centered systems.

For this purpose, the here presented paper proposed a bi-objective optimization for task allocation, aiming at minimizing both the time required to assemble the parts, including so the makespan minimization as objective function, and the energy required by the operator during the work. Multi-objective optimization has already been extensively studied, however, there is still no research concerning this for collaborative systems. Hence, the objective functions are described, followed by the problem statement with the constraints included. Moreover, characteristics indexes are analyzed to evaluate the performance of the method.

A case study is finally reported to demonstrate the practical implication of the research, proposing a different set of optimal solutions, which may be selected according to specific needs.

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1. Introduction

In the last years, the market is oriented towards the use of automation because of an increase of mass customization, [1], that requires more products' personalization with a decrease of their life cycle. In order to achieve this goal, technologies, such as collaborative robots (cobots), are used [2].

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However, this is typical of Industry 4.0, which is having an evolution in the so called Industry 5.0, with a human-centered design of the workplaces, [3]. In this perspective, the concept of Human-Robot Collaboration (HRC) is strengthening since cobots can replace operators in too burdensome tasks [4].

In order to achieve the best integration between the resources, i.e. operator and cobot, it is necessary to include, in the task allocation, different aspects concerning the operator's wellness. To do that multi-objective optimization could be of help. In the following lines, the state of the art regarding multi-objective task allocation is analyzed, in order to evaluate similar methodologies and the research gaps, in particular with regards to this topic for collaborative robot systems.

Initially, multi-objective problems were solved through the transformation of the multiple objectives into a single one, because of the absence of proper solving techniques, [5]. With the introduction of Pareto optimal solutions, it was possible to find a set of optimum, often showing some trade-offs, in order to make a better choice based on the results that have to be obtained. Starting from this, different multi-objective algorithms have been developed to evaluate various problems.

Multi-objective optimization is studied by different authors, that propose different solutions such as [6, 7], which focus on makespan and work-load smoothness index. The authors suggest, respectively, to resolve the optimization problem with Pareto Frontier and Particle Swarm Optimization algorithm (PSO).

Other studies are done by [8, 9], where through the use of Genetic Algorithm (GA), a multi-robot system is considered in order to optimize the allocation and the trajectories of these devices.

One solution that aimed at the cycle times minimization and operation alternations was presented by [10], where this was done in order to correctly alternate the jobs in order to promote the collaboration between the resources, placing the more and the less experienced near to each other, with the purpose of sharing the knowledge.

The first effort to introduce collaborative robot in assembly line balancing problem (C-ALBP) is proposed by [11], where, however, only one objective, that is the minimization of the makespan, has been considered.

A trade off between productivity, physical workload and mental workload was studied by [12] in order to integrate a cobot in a manual workplace. A theoretical framework was realized to evaluate which tasks could be substituted by the robot.

Another solution was proposed by Galin et al. [13], where the authors focused more only on increasing efficiency in Human Robot Collaboration (HRC). This paper drew some principles for the realization of a collective task allocation.

For the lack of integration of collaborative robots in multi-objective task allocation problems, a new method is here presented, with the aim to minimize both the total time required in the assembly process and the energy expenditure required by the operator. In the proposed work, the objectives and the constraints of the model are defined, proposing a resolution through the Pareto Frontier method. Secondly, a case study is analyzed in order to apply the method to an industrial scenario. The research goal is to find a solution that offers the best trade-off between the two objectives.

The model here described can have high practical implications in the industrial field, since it offers a solution that allows to obtain the best trade-off between productivity, in line with Industry 4.0 principles, and effort required to the operator, in order to respect the principles of Industry 5.0. In particular, here, the aspect focuses on the human-centered design of the workplace, linked to its resilience thanks to the re-adaptability of cobots, since they can be easily adapted to perform different types of tasks, [4]. Thereby, if it is necessary to change the process, it is not necessary to change the resources, implying a considerable saving.

Nomenclature

J	Number of tasks
j, p	Task index $j, p=1, \dots, J$
K	Number of resources
k	Resource index $k=1, \dots, K$
t	Temporal instant [s]
T	Temporal horizon [s]
E_p	Set of predecessors of task p
L_p	Set of successors of task p

$t_{j,k}$	Task time j for resource k [s]
x_{jkt}	Decision variable [0,1]
e_{jkt}	Energy for task j
ms	Makespan [min]
E	Energy expenditure [kcal/task]
ms^*	Single-objective makespan [min]
E^*	Single-objective energy expenditure [kcal]
$m_{\%}$	Makespan index
$e_{\%}$	Energy index
$c_{\%}$	Collaboration index
$p_{\%}$	Parallelism index
T_{coll}	Collaboration time [s]
d_{ut}	Distance from Utopia Point

2. Bi-objective task allocation

The here proposed task allocation is based on the resolution of the standard assembly line balancing problem, with the introduction of a collaborative robot (C-ALBP), [11]. The novelty of this work is that two objective functions are considered: makespan, i.e. the total time required to complete all the tasks, and energy expenditure, [14], i.e. the total amount of energy consumption required by the operator to complete the tasks assigned to him. The optimal set of solutions will be evaluated through *Pareto Frontier*, [15] and, as final solution, it will be chosen the one that has the minimum *Euclidean distance* from the *Utopia point*, Eq. 1, where both the objectives have value equal to 0, [16]. The objectives are normalized through their single-objective optimization values, i.e. ms^* is the makespan obtained if it is the only variable to be optimised and E^* is the energy obtained if it is the only variable to be optimised.

$$d_{ut} = \sqrt{\left(\frac{ms}{ms^*}\right)^2 + \left(\frac{E}{E^*}\right)^2} \quad (1)$$

Since a cobot is included in the work area, it is necessary to consider the safety problem, considering the standard regulation ISO/TS 15066 for collaborative robot [17], that specifies some security requirements, i.e. safety rated monitored stops, hand guiding, speed separation monitoring and power and force limiting. A cobot with these characteristics already integrated is used. This is done, since this paper, focuses on the resolution of a bi-objective task allocation and in the Pareto Frontier are included only the solutions that respect the safety requirements: safety is not neglected on behalf of the optimization.

2.1. Hypotheses

The assumptions made for the model are:

- single-model line, supposing that a mass production for one product that requires J operations is hypothesised. Alternatively, it can be considered that the single-model is a Virtual Average Model (VAM), derived from different product variants;
- task times are considered integer and deterministic;
- a single resource can execute one task at time and it has to conclude it before starting the next one;
- there is a single workstation with two resources, $K = 2$, i.e. a human operator and a cobot. This can be extended to more operators and cobots, in order to optimize multi-resources systems.
- the workstation is collaborative, that means the resources share the space and the time;

- no particular background is required to the operator, nor social or technical background, level of education, etc.;
- there are no technological constraints, since the cobot is equipped to perform all the tasks.

2.2. Makespan and Energy

The first objective function considered is makespan ms , that is the total time required to assemble the final product. The goal is the minimization of ms in order to increase the productivity, as required by Industry 4.0. That means:

$$\min ms = \min(\max T(x_{jkt}) - \min T(x_{jkt})) \quad (2)$$

In order to realize a human-centered task allocation, as Industry 5.0 suggests, [3], the second objective function introduced here is the minimization of operator's energy consumption. Energy expenditure rate is evaluated through the method proposed by [14], where, for each manual task, a required level of energy consumption is established, with the tables proposed. This division underlines which task is more burdensome for the operator.

However, the minimization of this objective is described by Eq. 3:

$$\min E = \min\left(\sum_{j=0}^J e_{jkt} \cdot x_{jkt}\right) \quad k = 1 \quad (3)$$

where e_{jkt} is the energy required to complete task j .

These two objectives are against each other, since the minimization of the first one implies to saturate more the resources leading to a substantial increase of the second one and vice versa.

2.3. Constraints

The two aforementioned objectives are subjected to:

$$\sum_{t=0}^T \sum_{k=1}^K x_{jkt} = 1 \quad \forall j \quad (4)$$

$$x_{pkt} \cdot T \leq x_{jkt} \cdot T \quad \forall j, \forall p \in E_p \quad (5)$$

$$x_{pkt} \cdot T \geq x_{jkt} \cdot T \quad \forall j, \forall p \in L_p \quad (6)$$

$$x_{jkt} \in \{0, 1\} \quad \forall j, k, t \quad (7)$$

where x_{jkt} is the result of the task allocation, i.e. the optimization variable:

$$x_{jkt} = \begin{cases} 1 & \text{if the task } j \text{ is performed by the resource } k \text{ at the time } t \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

and it conserves the *integrality* through Eq. 7.

The constraints introduced represent the *occurrence*, Eq. 4, meaning that for each temporal instant one resource can execute only one task; the *precedence*, Eq. 5,6, using the Patterson and Albracht method, ensuring that no task is assigned before its predecessors, [18].

2.4. Characteristics indexes

In order to evaluate the performance of the proposed method, different indexes for product and process characteristics defined in [11] are used and here recalled:

- *parallelism index* $p_{\%}$:

$$p_{\%} = 1 - \frac{\sum_{j=1}^J \frac{n_j}{J-1}}{J} \quad (9)$$

where n_j is the sum of the number of predecessor and successor tasks of j , i.e. it is the number of tasks that can not be carried out in parallel with j ;

- *collaboration parameter* $c_{\%}$:

$$c_{\%} = \frac{T_{coll}}{ms} \quad (10)$$

that is the ratio between the shared time T_{coll} , i.e. the time in which both the resources are working, and the makespan, [19].

Other indexes introduced are:

- *makespan index* $m_{\%}$:

$$m_{\%} = \frac{ms}{\min\{ms\}_{d_{ut,min}}} \quad (11)$$

that is an output parameter to evaluate the makespan with the proposed task allocation (*process* characteristic). It is the ratio between the actual makespan obtained and the one obtained when the distance from the utopia point is the minimum;

- *energy index* $e_{\%}$:

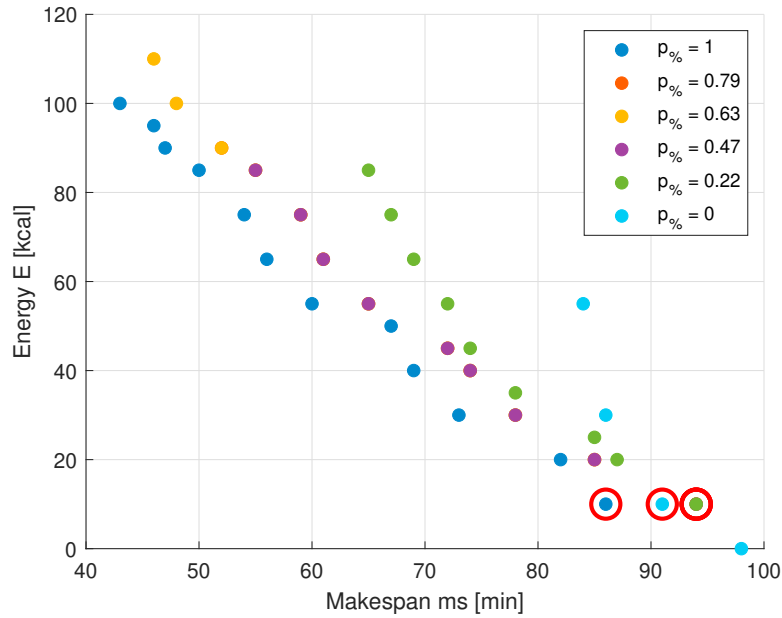
$$e_{\%} = \frac{E}{\min\{E\}_{d_{ut,min}}} \quad (12)$$

that is an output parameter to evaluate the level of energy expenditure with the proposed task allocation (*process* characteristic). It is the ratio between the actual energy level obtained and the one obtained when the distance from the utopia point is the minimum.

3. Case study

To test the model, an assembly process with $J = 10$ tasks is analyzed. This scenario is typical of collaborative assembly systems, that are having a great diffusion. This case study is for products consisting in small parts and, therefore, it is applicable to a wide variety of products.

The cobot used for this case study is a KUKA LBR iiwa 14 R820; however, this approach can be extended to each type of cobot, also multi-arm ones, by correctly considering their characteristics. For the operator, as stated in

Fig. 1: Effect of parallelism index $p\%$ on the Pareto Frontier.

the hypotheses, no particular background requirements are necessary. The computer used is a DELL-ALIENWARE R11, with Intel Core i7-10700KF CPU 3.80GHz and 32 GB of RAM; the algorithm used to solve the optimization is "gamultiobj" in MATLAB (Mathworks) environment and it has required about 1.58 hours for each result.

The tasks time, both for the operator and the cobot are obtained by [20], and they are reported, along with the energy expenditure, in Table 1.

Table 1: Tasks time and positions

Task	Operator Task Time (<i>min</i>)	Cobot Task Time (<i>min</i>)	Operator Energy (<i>kcal</i>)
1	5	12	10
2	13	13	35
3	13	5	35
4	8	13	20
5	12	10	30
6	5	4	10
7	8	6	20
8	13	9	35
9	11	13	25
10	13	13	35

Figure 1 shows the Pareto Frontiers based on the variation of the level of precedence imposed through the parallelism index $p\%$. The values considered are reported in Table 2, along with the tasks order, the values of ms and E obtained with that configuration and the division of the tasks among the resources, where "O" is for operator's tasks and "C" is for cobot tasks.

For all cases, the solutions that implied the assignment of all tasks to one resource are not considered because of the hypothesis previously made in Section 2.1.

Table 2: Parallelism index, Tasks order and proposed task allocation

$p_{\%}$ (%)	Precedence Order	Random Order	ms (min)	E (kcal)	O	C
1	-	[1,2,3,4,5,6,7,8,9,10]	86	10	[1]	[7,10,6,2,8,4,3,5,9]
0.79	$1 \rightarrow 2$	[3,4,5,6,7,8,9,10]	94	10	[6]	[1,2,3,5,4,7,8,10,9]
0.63	$1 \rightarrow 2, 3$	[3,4,5,6,7,8,9,10]	94	10	[6]	[1,2,3,8,9,4,7,10,5]
0.47	$1 \rightarrow 2 \rightarrow 3$	[4,5,6,7,8,9,10]	94	10	[6]	[1,2,3,4,5,9,10,8,7]
0.22	$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5$	[6,7,8,9,10]	94	10	[6]	[1,2,3,4,5,9,8,7,10]
0	$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow 10$	-	91	10	[1]	[2,3,4,5,6,7,8,9,10]

As it is possible to see from Figure 1 some frontiers may coincide, i.e. for $p_{\%} = 0.79$ and $p_{\%} = 0.63$. However, a decrease of parallelism index reduces the number of points of the frontier. This is because the possible combinations of the division of tasks between the resources decrease as the strictness of the precedence increases.

The solution here proposed is just one of the set obtained from Pareto Frontier, and it is possible to choose the one that best suits the needs.

3.1. Indexes evaluation

This section aims to present the evaluation of the indexes described in Section 2.4. The tests are carried out for the different values of $p_{\%}$, before described.

The first index analyzed is the makespan index $m_{\%}$: Figure 2 shows the effect of the distance from utopia point on it, for the different values of the parallelism index. The results are fitted with a 2-nd degree power interpolation with a bisquare robustness, that offers the best interpolation.

As it is possible to see, the index decreases with the increment of the distance, which means that further the point is away from utopia lower the makespan is. This is quite surprising because it is typical to believe that nearest the solution is to the utopia point, smaller should be the time required.

Quite the opposite is the influence of the distance on the energy index $e_{\%}$, as it can be seen from Figure 3. Like before, the results are fitted with a 2-nd degree power interpolation with a bisquare robustness. In this case, the energy increases with the increment of the distance, almost directly proportionally.

This is reasonable, if Figure 1 is analyzed: it can be viewed that, for all the cases considered, the scenarios with minimum distance from utopia point, represented with red circles, are placed on the bottom right of the figure. This means that the point that has minimum distance from the utopia one, for all $p_{\%}$ considered, has high makespan but low energy.

Collaboration index $c_{\%}$ is represented in Figure 4 where a 2-nd degree power interpolation was made. Similarly to $e_{\%}$, it increases, that means it raises with the distance from the utopia point. This is because, since the makespan decreases with the distance, the ratio between the shared time and ms is bigger.

For $p_{\%} = 0$, when all the tasks have to be carried out sequentially, the shared time is null for all the distances. This is due to the fact that the resources can not share tasks and each one has to be completed before the following one can be started.

It is also possible to conclude that $p_{\%}$ influences the other parameters quite in the same way, that means that it does not have greater influence on one index than on the others.

3.2. Other solution from Pareto Frontiers

In this section, other points of the Pareto Frontiers are evaluated, in order to analyze all the possible needs. The points considered, with the proposed task allocation, are reported in Table 3. As it is possible to see from the table, there are several optimal solutions. If it is preferred not to have long idle times for the operator, and so to have the minimum makespan, the best solution is the one that more parallelizes the tasks, in spite, however, of an increase of operator's energy expenditure. Vice versa, if the idle times and the makespan are not an issue, less tasks are assigned to the operator, lower his energy requirement is. In conclusion, as stated before, the trade-off to choose is the one that best suits the need.

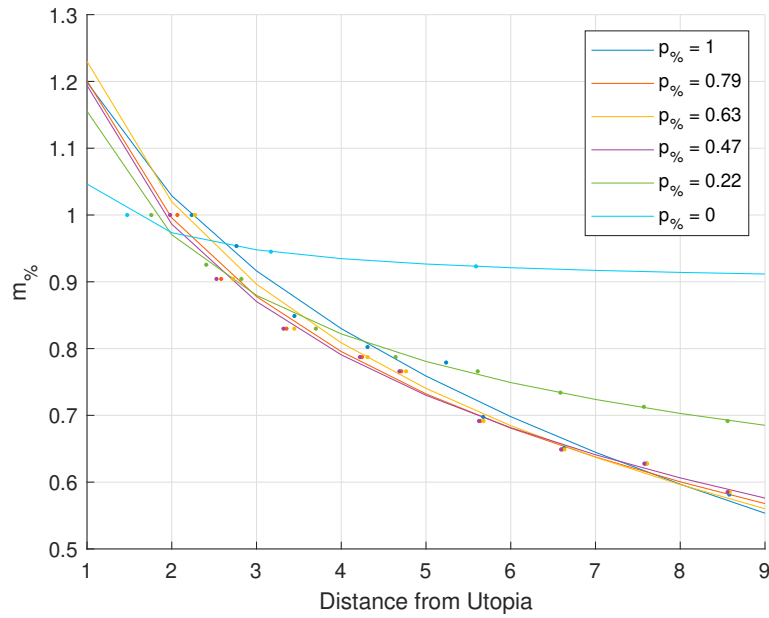


Fig. 2: Effect of the distance from utopia point on makespan index $m_{\%}$.

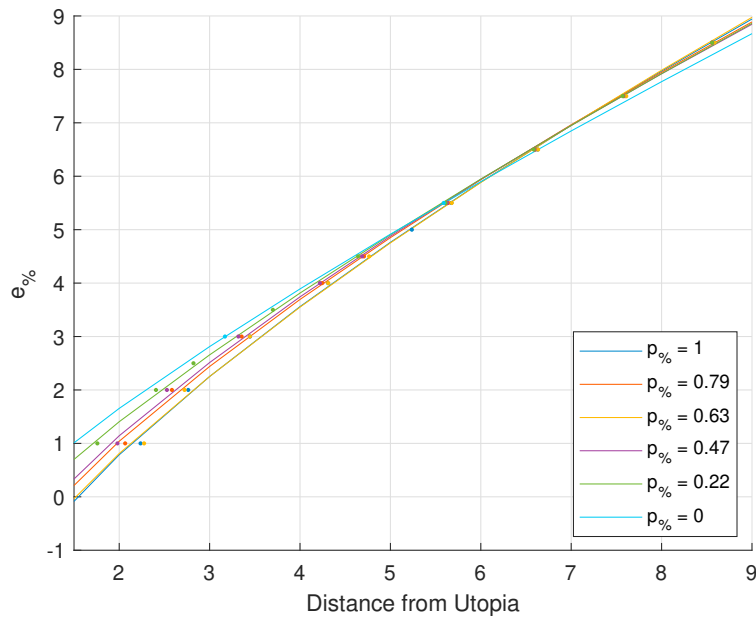


Fig. 3: Effect of the distance from utopia point on energy index $e_{\%}$.

4. Conclusion

Collaborative systems are a new technology, introduced in the last years, that can provide highly productive but also flexible systems. Nowadays, the focus is moving toward the wellness of the human operators that have to work

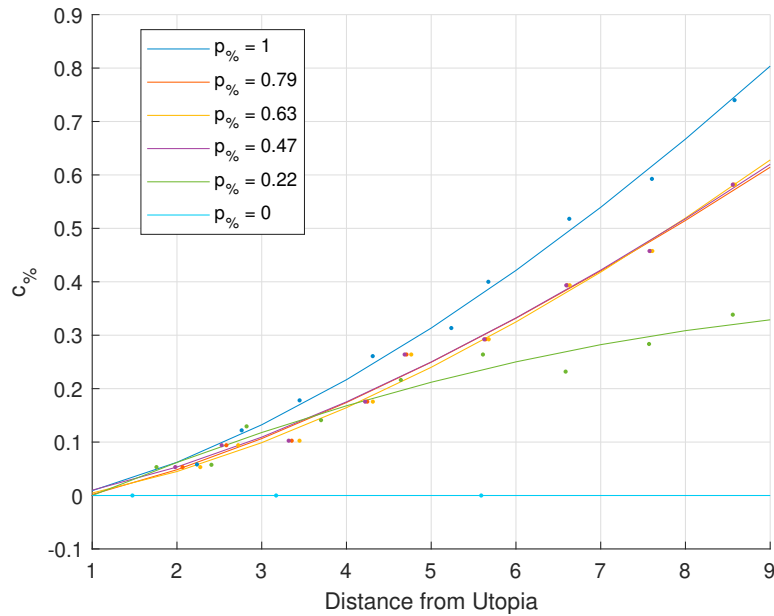


Fig. 4: Effect of the distance from utopia point on collaboration index $c\%$.

Table 3: Parallelism index, Tasks order and proposed task allocation

$p\%$ (%)	ms (min)	E (kcal)	O	C
1	43	100	[4,1,6,9,10]	[8,3,7,5,2]
1	60	55	[1,4,9]	[6,7,5,10,3,2,8]
1	73	30	[4,1]	[8,2,10,3,6,5,9,7]
0.79	52	90	[1,9,4,10]	[2,3,6,8,7,5]
0.79	65	55	[1,9,4]	[2,3,8,10,5,7,6]
0.79	78	30	[1,4]	[2,3,8,5,3,10,7,9,6]
0.63	46	110	[1,2,9,7,4]	[3,10,6,5,8]
0.63	65	55	[1,9,4]	[2,3,7,5,6,8,10]
0.63	78	30	[1,4]	[3,2,9,6,5,7,10,8]
0.47	55	85	[1,4,9,7,6]	[2,3,5,8,10]
0.47	72	45	[9,4]	[1,2,3,6,5,10,7,8]
0.47	78	30	[1,4]	[2,3,5,6,9,7,10,8]
0.22	65	85	[1,4,7,9,6]	[2,3,5,8,10]
0.22	74	45	[1,6,9]	[2,3,4,5,8,7,10]
0.22	78	35	[1,9]	[2,3,4,5,6,10,7,8]
0	84	55	[1,4,9]	[2,3,5,6,7,8,10]
0	86	30	[1,4]	[2,3,5,6,7,8,9,10]

directly with cobots, in order to guarantee the best human-robot collaboration. To achieve this, a new multi-objective task allocation model for cobot systems is presented, which considers makespan, for high productivity, and energy expenditure, for the operator's well-being.

This model proposes a balancing solution to reach the necessary trade-off between the two objectives, without neglecting the safety factor. From the analyzed case study, it is possible to understand that the trend of the two objective functions is divergent. Indeed, considering the Pareto Frontiers and the indexes evaluation, it is possible to conclude that the precedence does not have great influence on the objectives, while the distance from the utopia point substantially changes the value of the indexes analyzed.

The novelty of this work is the realization of a bi-objective task allocation including, as resources, a human operator and a cobot, when typically this problem is studied and solved for fully manual systems or fully automated ones. Moreover, the proposed solution offered a trade-off between the productivity and the operator's energy expenditure, promoting a better human-robot collaboration.

Starting from this, future development can be realized: more case studies could be analysed in order to carry out a sensitivity analysis and also, experimental tests could be carried out to verify the level of productivity and wellness that can be reached, in order to satisfy the principles of both Industry 4.0 and 5.0. Moreover, the time variability could be considered. This is due to the fact that operators may request different amount of time, than predicted, to perform a task and so, some uncertainties may arise. Finally, more objectives could be introduced in the model.

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