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# Economic and ergonomic performance enhancement in assembly process through multiple collaboration modes between human and robot

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## ABSTRACT

Collaborative robots have open new ways of designing assembly processes, thanks to their ability to share work space with operators. not only may they support the economical performance, but they can also improve the overall ergonomics. Building on existing work on task allocation problems, the authors study further the collaboration opportunities between operator and robot, namely cooperation phases (type of collaboration where both operator and robot act on the same work piece). This work proposes a new formulation of the related problem, and solutions are sought through heuristics methods, to investigate whether concurrent usage of different collaboration modes delivers better performance. The results indicate that cooperation mode enables higher process performances while controlling ergonomic risks. With a concern for real-life application, it has been applied on a real case study to verify its applicability.

## 1. Introduction

### 1.1. Background

Implementation of Collaborative Robotics represents a potential source of improvement for assembly processes in terms of operational efficiency. Their ability for safe integration in presence of human makes them valuable coworkers. Since there is no need for physical separation (along with appropriate safety measures), one may design smooth hybrid processes for human and collaborative robot, where allocation to either resource can be done at task level. If such configurations open way for economical performance enhancement, they should however be considered along-with some limitations for robot motion speed and ability to perform complex tasks.

Shifting from a purely economical performance perspective, ergonomic benefit may raise the attractiveness of hybrid processes. Delegating appropriate tasks to the robot may relieve the operator of awkward postures or fatigue from the repetition of load handling. In those conditions, designing such a process would result in solving a multiobjective task allocation problem among human and robot.

### 1.2. Proposal

Pushing further the use of collaborative robot technology, one could consider not only allocating tasks either to

operator or robot but also proposing a simultaneous joint action of robot and operator, splitting then the ergonomic load, while maintaining the dexterity and speed of the operator. This third possible type of allocation offers advantages for both economical and ergonomic performance: the overall task execution time is not extended (using operator time as a reference) since the operator speed can still be at use, and by splitting the task content appropriately, the ergonomic load for the operator may be significantly reduced. As a drawback, this option engages both resources, preventing possible parallelisation of another task during this sequence. Interestingly, the consideration of those two collaboration modes offers a three way trade-off (operator, robot, cooperation of both) where none of the selected mode dominates the two others on both performance objectives, as summarised in Table 1.

In this paper, the authors propose a set of solutions for this problem, focusing on the advantages of incorporating various collaboration modes. With a concern for real-life application, the proposed solutions will also be tested through real use cases, to confirm the relevance of the proposed model, hence offering valuable tools for practitioners.

The rest of this article is structured as follows: Section 2 will review existing literature on comparable problems and related resolution methodologies.

**Table 1.** Qualitative comparison of collaboration modes under performance criteria.

	Operator	Robot	Cooperation
Eco. performance	High	Low	High
Ergo. performance	Low	High	Intermediate
Parallelisation of tasks	High	High	Low

Section 3 will define a model and detail the strategy of resolution. Section 4 will review the obtained results, and finally Section 5 will conclude this paper and open on further possible work.

## 2. Literature review

Through the description of the considered problem, two main issues emerged:

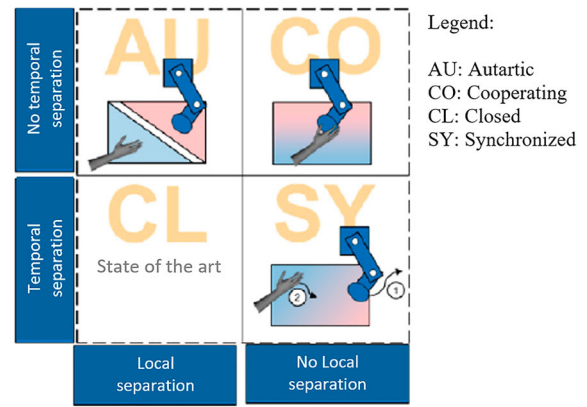
- Interaction between human and robot
- Assignment of tasks between those resources to improve a double criteria: economic and ergonomic.

In the current section, a literature review about these issues is done.

### 2.1. Human–robot interaction

Several types of safe interactions can be foreseen in the context of assembly operations, ranging from physical separation between operators and robot to simultaneous action on the same work piece. Classifications are based on spatial and temporal separation, see Thiemermann (2005), Matheson et al. (2019), describing comparable interactions, despite use of different names, see Figure 1 for Thiemermann representation. A more refined model has been proposed by Aaltonen, Salmi, and Marstio (2018), which includes additional factors such as goal sharing or possibility of physical contact between operator and cobot. In the present work, the model presented in Figure 1 delivers sufficient accuracy and its terminology will be used throughout this paper.

In terms of assembly process, the so-called synchronised mode indicates that operator and robot are working on their respective task in parallel, providing their selection satisfies related constraints, typically precedence of tasks, or feasibility in case of robot allocation. In such case the ergonomic load is fully removed from the operator, but at the expense of a longer completion time, since it is generally observed that robot motion is reduced when sharing working space with human, impairing then economical performance (cycle time or makespan). Regarding actual cooperation, the resulting ergonomic gain depends on the way the work elements of the task have been split, with regard to the ergonomic model selected.



**Figure 1.** Human robot interaction categories, adapted from Thiemermann (2005).

Due to the intentional proximity between operator and robot, a special attention has to be given to safety conditions during the process design phase. As stated in ISO 15066,

Robot motion speed has to be controlled to comply with energy limitation in case of collision.

Various activity scopes can be seen when designing a collaborative workplace, depending on the extent of the influencing factors considered, as stated by Simões et al. (2022). Most complex scenarios include human and social factors, whereas the simplest ones focus solely on the constituents (operator or cobot). Intermediate levels focus on process performance and therefore incorporate several factors such as task allocation strategy, ergonomic cost and task duration and feasibility by each resource. Multi-objective approaches exist, following a sequential process starting from breaking down the work content in tasks, whose feasibility by each resource is then assessed, based on complexity, ergonomic cost, or requirement for specific equipment (Gjeldum et al. 2021; Pini, Leali, and Ansaloni 2015). Malik and Bilberg (2019) propose a more gradual approach where tasks rather have an affinity score for allocation towards operator or robot, based on the above-mentioned factors. Generally, tasks are then allocated to the idle resource (Tsarouchi et al. 2017; Faber, Bützler, and Schlick 2015). In brief, design of collaborative workplace may encompass several aspects with different levels of details. When considering process performance aspects, the proposed strategies are mainly sequential and offer little possibility of optimisation for allocation and sequencing, especially considering joint usage of both resources (cooperation mode).

The gap we intent to address is to take the best advantage of multiple collaboration modes to design an optimal process in terms of economical performance and

ergonomic risk. In that purpose, allocation problems will also be reviewed, as close situation this work, to identify transferable optimisation strategies in comparable models.

## 2.2. Allocation problems

The studied problem in the current paper is an allocation problem: the main objective is to allocate every task to some resource (worker, robot or both), respecting precedence constraints and minimising costs (economic and ergonomic). Both scheduling and line balancing problems deal with allocation consideration.

### 2.2.1. Scheduling

Scheduling problems have been widely studied in the literature for many years. In the following, the case of Unrelated Machines and Resource Constrained Project Scheduling Problems (RCPS) are detailed among all scheduling problems, because these two consider several different resources, as in the problem studied in this paper.

*Unrelated Parallel Machines (PMS)*. connect to the problem studied in this paper since the processing time of a task depends on the machine to which it is allocated. Although this problem has been less investigated than identical parallel machine scheduling, several methods have been proposed to solve it, ranging from exact algorithms (Rocha et al. 2008; Wang and Ye 2019), to heuristics (Herrmann, Proth, and Sauer 1997; Fanjul-Peyro and Ruiz 2011; Wang and Bahram 2019) and metaheuristics like ant colony (Lin, Hsieh, and Hsieh 2012), simulated annealing (Kim et al. 2002; Lin and Ying 2015) or genetic algorithms (Nikabadi and Naderi 2016; Vallada and Ruiz 2011).

In parallel machine scheduling problems, the most widely studied objective is the makespan. Some papers also have multi-objective considerations where jobs' tardiness is taken into account (Pfund, Fowler, and Gupta 2004). However, to the best of our knowledge, the ergonomic aspect has never been dealt with in this issue. Moreover, there is a major difference between our problem and parallel machine scheduling: in our problem, a task can be performed simultaneously by both of the operator and the robot, while in parallel machine scheduling a job cannot be by allocated to more than one machine. We are thus facing additional constraints and challenges.

*RCPS*. represents scheduling problems with resources allocation. There are precedence constraints between

tasks. Resources in a given quantity are needed to process a task. Usual hypothesis about RCPS are the following.

- Resources are renewable: resources are returned at the end of the execution of a task and thus become available again to realise other task.
- Resources can be of several types, they are available in a given quantity over the entire time horizon.
- Tasks are non-preemptive, once started they cannot be interrupted.
- Tasks are subject to precedence constraints.
- Tasks require the same amount of resources throughout their execution time.

Several RCPS models exists. The considered case study in the current paper can be seen as a Multi-Mode RCPS (MRCPS). Mode defines the execution mode for each task: an execution time plus a quantity of resources for each type of resource. In MRCPS, several modes can be used to process each task. Tasks require a variable number of resources, and execution time depends on the number of assigned resources. MRCPS has been introduced by Elmaghraby (1977). Its resolution has drawn attention from researchers (Van Peteghem and Vanhoucke 2010), extensive literature reviews have been realised on this problem by Yang, Geunes, and O'brien (2001) and Hartmann and Briskorn (2010). Kolisch and Sprecher (1997) propose a mathematical model to model MRCPS.

Most of the papers about MRCPS deal with economic objectives (makespan minimisation). None of them considers the ergonomic objective, in the case of allocation of tasks to worker or robot or both of them.

### 2.2.2. Line balancing

Assembly Line Balancing Problems (ALBP) and their multiple extensions cover a wide range of situations, but share common characteristics that enable them to be described and classified in several categories (Battaia and Dolgui 2013), (Boysen, Fliedner, and Scholl 2007). The purpose of this section is to identify potential similarities between the studied problem and previous research, to help building an appropriate modelling and collect insights on applicable resolution methods.

Although it may not seem initially appropriate to include line balancing problems in the context of single station, one may notice that in the case of synchronised mode (see Figure 1, two following products can be transformed simultaneously by the operator and cobot in two different workplaces. Therefore, this condition is comparable to a 2-station line where workload has to be best balanced between operator and cobot, to minimise the overall cycle time. Nevertheless, this possibility of

overlapping between following products affects the calculation of the economical performance, which will be reflected in the following section.

The studied environment, featuring a single station, is not fit for SALBP type-1 resolution. Type 2 resolution may be suitable, as cycle time is considered as the economic target to be minimised. Characterising this problem from an ALBP perspective leads to consider the following elements :

- Resources are heterogeneous: Robot cannot be assigned to every task, and its completion time for a given time is higher than operator.
- Most tasks can be performed by simultaneous usage of both resources (cooperation), which affects their completion time and ergonomic cost.
- Both ergonomic and economic performances are set as objectives.

Implementing robots in place of operators at workstations has been reflected in RALBP (Robot Assembly Line Balancing Problem), where Task Times are dependant of the selected robot. Robots do not necessarily have the ability to perform every task (Rubinovitz, Bukchin, and Lenz 1993). Such work may be seen as a particular case of heterogeneous manpower, which has been further studied in ALWABP (Assembly Line Worker Assignment Balancing Problem), with application towards Sheltered Work Centres for Disabled (Moreira et al. 2015; Borba and Ritt 2014; Moreira et al. 2012; Miralles et al. 2007). Operator and robot may be considered indeed as heterogeneous manpower, having distinct abilities and task times. However, robot being slower than operator, the only economical benefit in its introduction is based on parallelisation of task, and its ability to cooperate with operator. Parallelisation of tasks in a single workstation has been studied in ALBP literature, as in double-sided lines or Variable Workplace Assembly Line Balancing Problem (VWALBP). such models are used for large size products where several operators (workplaces) can be affected to the same workstation (Becker and Scholl 2009). In such conditions, task assignment is constrained by their related mounting position on the product, including the necessity to avoid obstruction between operators. Therefore simultaneous cooperation on same task is not considered.

Ergonomics has also been studied as an objective of line balancing problems, as a possible continuation of ALWABP, when used to describe environment with disabled workforce. Several methods issued by practitioners have been reflected by Otto and Scholl (2011) to evaluate the ergonomic risk for an operator based on posture, effort or carried load during the studied process. Such

problems – named ErgoALBP – tend to minimise the ergonomic risk across a determined number of stations. One of the difficulties when trying to balance ergonomic risk with economic cost is to estimate an impact of the former on the latter. Part of the answer has been brought by the Predetermined Motion Energy Systems (PMES) (Battini et al. 2016). In this model, ergonomic impacts of tasks are expressed as relaxation time, hence of the same dimension of the economic cost. This methodology relies on the calculation of the energy spent by the operator to perform necessary movements, maintain his posture, and carry out process tasks, considering the associated load due to components handling. In case of single workstation, operator remains static, so focus will be put on achievement of fatigue reduction through optimisation of components handling. Such model has been used by Weckenborg and Spengler (2019) to study economic and ergonomic benefit of introducing collaborative robots on a manual line. In a comparable approach, although using different ergonomic model, Pearce et al. (2018) suggested both economic cost and ergonomic risk could be reduced in a real-life assembly process, by sharing task appropriately between operator and robot. Both works considering task could be affected to operator or robot, but not the possibility of them cooperating on a same task.

In conclusion, it appears that the cooperation mode between operator and robot has been scarcely studied, especially in conjunction with its inherent benefits towards prevention of ergonomic risk while maintaining potentially high economical performance, as it can be seen in Table 2.

### 3. Proposition of resolution method

In the previous section, it has been shown that the studied problem is an extension of MRCPS or SALBP (with one station). These classical problems are NP-Hard problems, it does not exist any algorithms to solve these problems in a polynomial time. Our problem is an extension as it considers ergonomic aspect in addition to classical economic criteria. Thus the considered problem is also NP-Hard. In the following, proposed approximate method is presented.

#### 3.1. Objective function

The proposed method will be used on the twelve generated instances. The application of a method allows to define a solution  $X$ : the schedule of tasks with their assignment to resources (operator, robot, both). An assignment solution  $X$  provides operator's and robot's respective cycles times  $CT_O(X)$  and  $CT_C(X)$  (defined as 'the time when the operator, resp the robot, finishes his



**Table 2.** Summary of literature review.

Paper	Category	Objective type	Constraints					Solving method
			Ergonomy	Heterogenous manpower	Precedence	Setup times	H-R cooperation	
Becker and Scholl (2009)	VWABLP	Single	–	✓	✓	–	–	Exact
Borba and Ritt (2014)	ALWABP	Single	–	✓	✓	–	–	Exact
Fanjul-Peyro and Ruiz (2011)	PMS	Single	–	✓	✓	–	–	Meta heuristic
Herrmann, Proth, and Sauer (1997)	PMS	Single	–	✓	✓	–	–	Heuristic
Kim et al. (2002)	PMS	Single	–	✓	–	✓	–	Metaheuristic
Lin, Hsieh, and Hsieh (2012)	PMS	Multi	–	✓	–	–	–	Metaheuristic
Miralles et al. (2007)	ALWABP	Single	–	✓	✓	–	–	Exact
Moreira et al. (2012)	ALWABP	Single	–	✓	✓	–	–	Heuristic & Meta Heuristic
Moreira et al. (2015)	RALWABP	Single	–	✓	✓	–	–	Exact
Nikabadi and Naderi (2016)	PMS	Multi	–	✓	✓	✓	–	Metaheuristic
Otto and Scholl (2011)	Ergo ALBP	Multi	✓	–	✓	–	–	Heuristic
Pearce et al. (2018)	Ergo ALBP	Multi	✓	✓	✓	–	–	Exact
Quenehen et al. (2020)	–	Multi	✓	✓	✓	–	✓	–
Rocha et al. (2008)	PMS	Multi	–	✓	–	✓	–	Exact
Rubinovitz, Bukchin, and Lenz (1993)	RALBP	Single	–	✓	✓	–	–	Heuristic
Vallada and Ruiz (2011)	PMS	Single	–	✓	–	✓	–	Meta heuristic
Van Peteghem and Vanhoucke (2010)	MRCPSP	Single	–	✓	✓	–	✓	Metaheuristic
Wang and Bahram (2019)	PMS	Single	–	✓	–	–	–	Metaheuristic
Wang and Ye (2019)	PMS	Single	–	✓	–	–	–	Exact
Weckenborg and Spengler (2019)	ALWABP	Multi	✓	✓	✓	–	–	Exact

last task'), and the required relaxation time  $R_{tot}(X)$  for the operator. Two criteria are considered:  $C_{eco}$  the economic cost and  $C_{ergo}$  the ergonomic cost, given in Equations (1). The results are compared through the following objective function, defined in (2), where  $\alpha \in [0, 1[$  stands for a given trade-off between ergonomic and economic cost. More explanations are given by Quenehen et al. (2020).

$$\begin{cases} C_{eco}(X) = \max \{CT_O(X), CT_C(X)\} \\ C_{ergo}(X) = \max \{0, R_{tot}(X) - (C_{eco}(X) - CT_O(X))\} \end{cases} \quad (1)$$

$$H_\alpha(X) = (1 - \alpha) \cdot C_{eco}(X) + \alpha \cdot C_{ergo}(X) \quad (2)$$

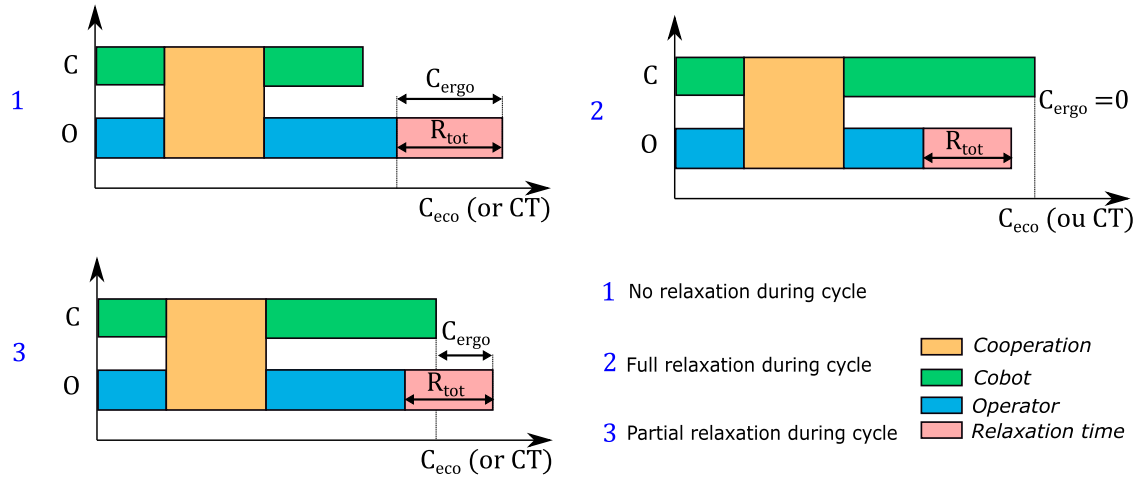
$C_{eco}$  corresponds to the makespan required for assembly operation, and is solely depending on which resource finishes last.  $C_{ergo}$ , however, is affected by the value of  $R_{tot}(X)$  and the gap between  $CT_O(X)$  and  $CT_C(X)$ . This may generate three possible cases as detailed in Figure 2.

### 3.2. Determination of economic and ergonomic costs in real case study

Several ergonomic models may apply to assembly processes (Otto and Scholl 2011), they consider have in common considerations for posture, extreme joint positions,

load carried, movement and vibration, and applied force as main criteria. Intensity and frequency of exposure to those risks are also impacting the ergonomic evaluation. Output result may be expressed as an index or a score, as per RULA (Rapid Upper Limb Assessment) (McAtamney and Nigel Corlett 1993), or as a relaxation time at the end of the assembly cycle as proposed by PMES (Battini et al. 2016, 2017). In the present work, this latter model will be considered to assess the case study, since it delivers the ergonomic cost in the same dimension as economic cost. This feature may have significant impact when using or not the time available at end of cycle for rest or starting up the next assembly.

In the present work, PMES model has therefore been selected and used on a real case study. With a fully manual process as a start point, process has been run until total cycle time became stable (learning curve of operator). Then five consecutive cycles are video recorded and broken down into elementary operations, for each of them the mean duration value is kept as a reference. Likewise for ergonomic cost, each movement from each elementary operation is assessed according to the tables provided by Battini et al. (2016), to determine the value of the associated relaxation time, if applicable.<sup>1</sup> Tasks



**Figure 2.** Possible formulations for  $C_{ergo}$  based on process configuration.

are then generated, as grouping of consecutive elementary operations that practically needs to be done by the same resource (e.g. picking and setting of screw). To populate Task Times for robots, a multiplying factor is applied from the manual task times, according to the experimental findings of Quenehen, Pocachard, and Klement (2019) in a comparable case study. In case the task cannot be completed by the robot, the time value is set to  $\infty$ . To determine both task times and relaxation time for the cooperation mode, each individual task is performed using both robot and operator, leaving the handling of the heaviest component to the robot (as a rule to minimise ergonomic cost). Then the same video capture process as per manual task is applied. If the task has no benefit from cooperation mode (e.g. picking of a single component), its task and relaxation times are set to  $\infty$ . Results for the case study can be seen in Figure 6.

### 3.3. Impact of overlap on objective function

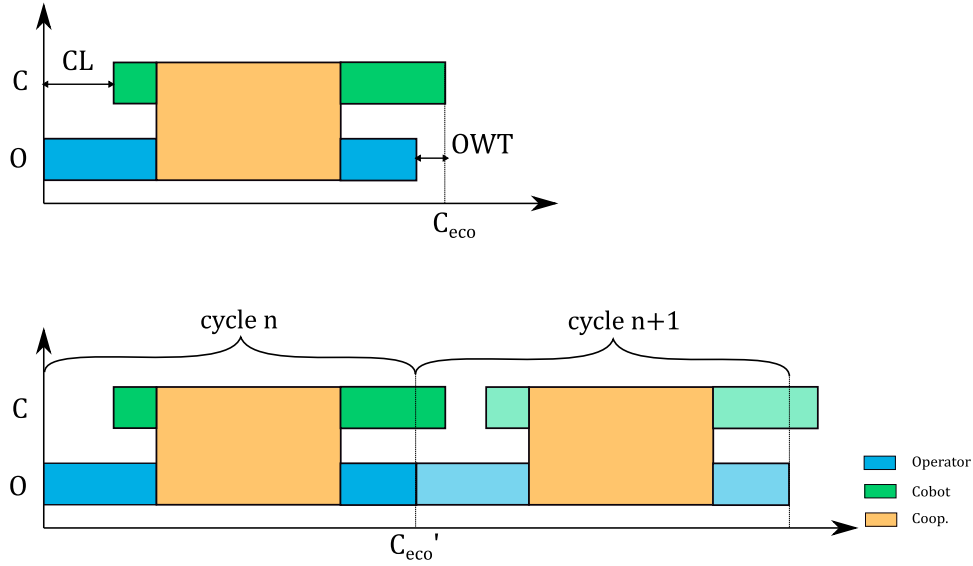
As mentioned in Section 2.2.2, the usage of synchronised mode at the end or beginning of the assembly cycle will create an opportunity for the idle resource to kick off the next product to assemble, which may naturally be used in that purpose in real life, see Figure 3. The operator idle time at the end of the cycle will be named Operator Waiting Time (OWT), respectively Cobot Waiting Time (CWT) for the cobot. The time available at the beginning of the cycle due to the late start of the cobot will be referred to as Cobot Lag (CL), respectively, Operator Lag (OL) for the operator. Depending on the respective values of those variables,  $C_{eco}$  and  $C_{ergo}$  may be affected, resulting in new cost values:  $C'_{eco}$  and  $C'_{ergo}$ . Different configurations and their impact are illustrated in Figure 4.

### 3.4. Approximate method development

For such range of instance, heuristic methods have proven efficient to propose solutions. Usual heuristics affect tasks to the first available resource, which is not suitable to test the cooperation mode since it may only be triggered in the unlikely eventuality of both resources being available at the exact same time. To visualise the effects of the three considered modes, a probabilistic allocation has been selected. For each task, a number  $R$  is randomly generated between 0 and 1, and two limit values  $L1$  and  $L2$  are set. If  $R < L1$ , task is assigned to the operator, if  $L1 \leq R < L2$ , task is affected to cobot, and if  $R \geq L2$ , the task is allocated to the cooperation mode, i.e. cobot and operator simultaneously. This heuristic  $L$  is given by Algorithm 1. Tasks are assigned according to precedence's constraints.

By nature, a heuristic gives an approximate solution. By coupling it to a metaheuristic, better solutions may be found, since a set of solution will be tested, instead of a single one. This principle has first been proposed by Gourgand, Grangeon, and Klement (2014) and more recently applied to several industrial applications in Klement and Silva (2020). The principle is illustrated in Figure 5.

The metaheuristic goes through the space of solutions, considering lists  $Y$  of tasks, using a neighbourhood system  $V$ . Each considered list  $Y$  of tasks gives an assignment solution  $X$  thanks to the list algorithm  $L$ , whose cost is assessed using the overlap function described in Figure 4. Then, this solution is evaluated thanks to an objective function  $H$ . The metaheuristic then generates a new list  $Y'$  from the current one, using the neighbourhood system  $V$ . In the developed method, a swap between two tasks is used as a neighbourhood system. The tasks of this new list  $Y'$ , the neighbour, are then



**Figure 3.** illustration of overlap between production cycles.

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**Algorithm 1:** Heuristic  $L$  to assign task to resources

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**Data:** List of task, precedence matrix, task time and recovery time according to the resource,  $L1$  and  $L2$

```

1 while All tasks are not assigned do
2   for Each task in a list do
3     if All the precedence tasks have previously be
       done then
4       Let  $R$  randomly and uniformly
         generated between 0 and 1
5       if  $R < L1$  then
6         Assign this task to the operator
7       else if  $L1 \leq R < L2$  then
8         Assign this task to the robot
9       else
10        Assign this task to the cooperative
          mode
11     else
12        Put this task at the end of the list

```

---

assigned thanks to the heuristic  $L$ , to give a solution  $X'$ . This solution  $X'$  is then evaluated using the objective function  $H$ . Finally both solutions (the current  $X$  and the neighbour  $X'$ ) are compared using the principle of the chosen metaheuristic. Algorithm 2 illustrates this hybridisation using the simulated annealing as a metaheuristic.

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**Algorithm 2:** Principle algorithm of the hybridisation between a list algorithm and the simulated annealing

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**Data:** Temperature  $T_0$ , decreasing factor  $\beta$ ,  
Maximum number of iterations  $IterMax$ ,  
Initial solution  $Y \in \Omega'$

```

1 iter := 0,  $T := T_0$ 
2  $X := L(Y)$ : apply the list algorithm to the list  $Y$ 
3 Record solution  $RY := Y, RX := X$ 
4 while iter <  $IterMax$  do
5   Choose randomly and uniformly  $Y' \in V(Y)$ 
6    $X' := L(Y')$ 
7   if  $H(X') < H(RX)$  then
8      $RY := Y'$ 
9      $RX := X'$ 
10  else if  $H(X') \leq H(X)$  then
11     $Y := Y'$ 
12     $X := X'$ 
13  else
14     $Y := Y'$  and  $X := X'$  with the probability
       $e^{-\frac{H(X')-H(X)}{T}}$ 
15  iter := iter + 1
16  Generate a new temperature  $T := \beta \times T$ 

```

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### 3.5. Instance generation

A set of instances is necessary to test both algorithm capability and benefit of multiple mode usage. Therefore 12 random test instances have been generated by a special



WT	CL	OL	Waiting time vs Lag	Schéma	$C'_{eco}$	$C'_{ergo}$
OWT > 0 (CWT = 0)	$CL = 0$	$OL \geq 0$	$OWT > CL$ A1		$C'_{eco} = C_{eco}$	$C'_{ergo} = \max\{0, R_{tot} - (OWT + OL)\}$
	$CL > 0$	$OL = 0$	$OWT \geq CL$ A2		$C'_{eco} = C_{eco} - CL$	$C'_{ergo} = \max\{0, R_{tot} - (OWT - CL)\}$
	$CL > 0$	$OL = 0$	$OWT < CL$ A3		$C'_{eco} = C_{eco} - OWT = CT_0$	$C'_{ergo} = R_{tot}$
OWT = 0 & CWT = 0	$CL = 0$	$OL \geq 0$	$CWT \leq OL$ B1		$C'_{eco} = C_{eco}$	$C'_{ergo} = \max\{0, R_{tot} - OL\}$
	$CL > 0$	$OL = 0$	$OWT \leq CL$ B2		$C'_{eco} = C_{eco}$	$C'_{ergo} = C_{ergo} = R_{tot}$
CWT > 0 (OWT = 0)	$CL > 0$	$OL = 0$	$CWT > OL$ C1		$C'_{eco} = C_{eco}$	$C'_{ergo} = C_{ergo} = R_{tot}$
	$CL = 0$	$OL \geq 0$	$CWT > OL$ C2		$C'_{eco} = C_{eco} - OL$	$C'_{ergo} = R_{tot}$
	$CL > 0$	$OL > 0$	$CWT \leq OL$ C3		$C'_{eco} = C_{eco} - CWT = CT_c$	$C'_{ergo} = \max\{0, R_{tot} - (OL - CWT)\}$

Figure 4. Alteration of  $C_{eco}$  and  $C_{ergo}$  according to process configuration.

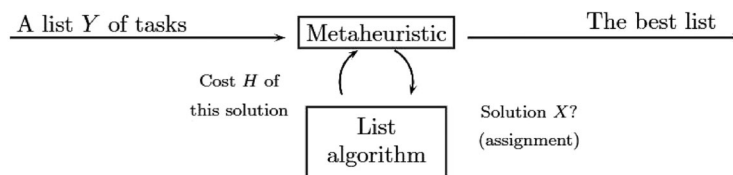
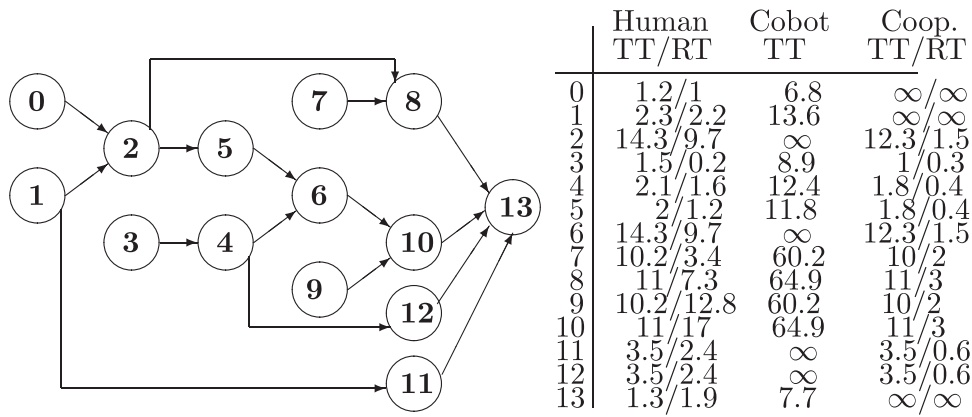


Figure 5. Hybridisation metaheuristic – List algorithm.



**Figure 6.** Precedence graph of our problem, with Task Time (TT) and Relaxation Time (RT) in seconds for each type of task assignment.

**Table 3.** Test instances.

	Order strength	
	$\in [0.1; 0.3]$	$\in [0.3; 0.5]$
[15–20] tasks	SosSt1	BosSt1
	SosSt2	BosSt2
	SosSt3	BosSt3
[20–25] tasks	SosBt1	BosBt1
	SosBt1	BosBt1
	SosBt1	BosBt1

purpose algorithm, as extensions of the original real case study represented in Figure 6.

Problem is meant for single station, so the number of tasks should be limited (14 in case study for instance). Therefore two intervals have been used, [15, 20] and [20, 25], to generate the number of tasks with a uniform distribution. Each task has approximately four to six predecessors at most, which represents a realistic assembly process. These precedence constraints also feature a final node.

The task times of the operator are generated with a uniform distribution in the interval between 1 and 15 seconds. The  $k$  pace ratio between operator and robot for each task is derived from observed values in case studies and is picked randomly in the interval [4, 6]. Likewise for the determination of task time of cooperative mode, values will be randomly picked in the interval [0.7, 1] of the corresponding manual task time.

Around 28% and 21% of the generated tasks are respectively not feasible by robot, or no fit for the cooperative mode. These percentages are centred on average value from real life examples. For these tasks, the processing time with robot or cooperation will be set to *infinite* value.

The order strength and the maximum order are also recorded for each generated instance. In total four families of instances, based on their number of tasks and

order strength, will be used to evaluate the proposed algorithm performances. In each family, three randomly generated instances are tested.

Table 3 summarises the 12 generated instances, with their respective name. These instances will then be used to experiment the proposed method.

## 4. Results

In this section, experimentation is detailed. First, the proposed approximate method is applied. Then, results will be checked by programming the sequence using collaborative robot and operator, to test the relevance of the proposed model and solving tool in real life situation.

### 4.1. Application on test instances

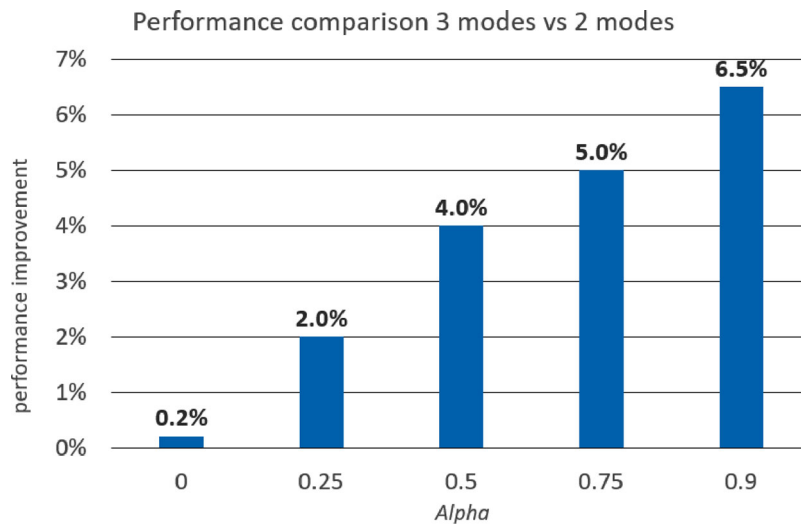
Validation tests are necessary to prove both the capability of the proposed algorithm and the benefit of using all collaboration modes. To this purpose, test instances have been generated as extension of observed real case. Due to its probabilistic nature for task allocation, the algorithm has to be run multiple times to reach any conclusion. Moreover, the task allocation may be influenced by parameters  $L1$  and  $L2$ , therefore several pairs of  $L1&L2$  are to be tested (0.5&0.75, 0.25&0.5, 0.33&0.66, 0.6&0.7 have been used). Only the best solutions of the multiple runs for every pair are recorded. Similar procedure is used to test solutions without cooperation mode, by setting  $L2$  value to 1. No dominant pair  $L1&L2$  has been identified for all test instances and all values of  $\alpha$ . Each result has been computed in less than 10 seconds using a 2.4 Ghz processor. The used metaheuristic is the simulated annealing presented by Algorithm 2, hybridised with heuristic given by Algorithm 1, with  $IterMax = 100000$ . Parameters  $T$  temperature and  $\beta$  decreasing factor have been generated using algorithms

**Table 4.** Results for test instances, IR stands for Improvement Ratio.

Alpha	0			0.25			0.5			0.75			0.9		
	3	2	IR	3	2	IR	3	2	IR	3	2	IR	3	2	IR
<b>Instance</b>															
<i>H</i>	123.3	121.9	<b>0.0%</b>	112.75	114.1	<b>1.2%</b>	89.8	94.00	<b>4.5%</b>	45.975	46.875	<b>1.9%</b>	18.45	19.01	<b>2.9%</b>
<i>C<sub>eco</sub></i>	123.3	121.9		125.7	125.2		172.8	184.50		183.9	186.9		184.5	190.1	
<i>C<sub>ergo</sub></i>	90.8	92.2		73.9	80.8		6.8	3.50		0	0.2		0	0	
<b>Instance</b>															
<i>H</i>	127.5	126.4	<b>0.0%</b>	121.4	121.7	<b>0.2%</b>	100.8	104.45	<b>3.5%</b>	53.75	53.075	<b>0.0%</b>	20.22	21.5	<b>6.0%</b>
<i>C<sub>eco</sub></i>	127.5	126.4		129.8	126.4		171.9	208.60		215	206.6		202.2	215	
<i>C<sub>ergo</sub></i>	102.2	107.6		96.2	107.6		29.7	0.30		0	1.9		0	0	
<b>Instance</b>															
<i>H</i>	139	138.2	<b>0.0%</b>	119.6	128.625	<b>7.0%</b>	99.35	105.55	<b>5.9%</b>	49.75	52.925	<b>6.0%</b>	20.69	21.17	<b>2.3%</b>
<i>C<sub>eco</sub></i>	139	138.2		135.7	139.1		155.9	211.10		199	211.7		206.9	211.7	
<i>C<sub>ergo</sub></i>	84.3	100.5		71.3	97.2		42.8	0.00		0	0		0	0	
<b>Instance</b>															
<i>H</i>	105.8	105.8	<b>0.0%</b>	104.125	104.15	<b>0.0%</b>	86.35	93.35	<b>7.5%</b>	43.05	46.075	<b>6.6%</b>	17.23	18.7	<b>7.9%</b>
<i>C<sub>eco</sub></i>	105.8	105.8		108.2	106		172.7	186.70		172.2	184.3		172.3	187	
<i>C<sub>ergo</sub></i>	107.6	107.6		91.9	98.6		0	0.00		0	0		0	0	
<b>Instance</b>															
<i>H</i>	112.1	113.1	<b>0.9%</b>	99.75	102.575	<b>2.8%</b>	79.75	84.15	<b>5.2%</b>	40.05	42.475	<b>5.7%</b>	16.05	17.1	<b>6.1%</b>
<i>C<sub>eco</sub></i>	112.1	113.1		116.9	113.9		159.5	160.60		157.8	167.5		160.5	171	
<i>C<sub>ergo</sub></i>	77.5	73.5		48.3	68.6		0	7.70		0.8	0.8		0	0	
<b>Instance</b>															
<i>H</i>	124.6	123.6	<b>0.0%</b>	119.825	119.225	<b>0.0%</b>	98.05	103.00	<b>4.8%</b>	50.975	51.5	<b>1.0%</b>	19.61	20.6	<b>4.8%</b>
<i>C<sub>eco</sub></i>	124.6	123.6		127	125		196.1	206.00		203.9	206		196.1	206	
<i>C<sub>ergo</sub></i>	120.3	110		98.3	101.9		0	0.00		0	0		0	0	
<b>Instance</b>															
<i>H</i>	158.4	151.2	<b>0.0%</b>	143.75	138.875	<b>0.0%</b>	115.7	111.90	<b>0.0%</b>	60.075	56.775	<b>0.0%</b>	23.83	22.65	<b>0.0%</b>
<i>C<sub>eco</sub></i>	158.4	151.2		164	151.2		207.7	223.80		240.3	227.1		238.3	226.5	
<i>C<sub>ergo</sub></i>	94.1	101.9		83	101.9		23.7	0.00		0	0		0	0	
<b>Instance</b>															
<i>H</i>	125.1	124.1	<b>0.0%</b>	110.625	114.925	<b>3.7%</b>	93.25	96.65	<b>3.5%</b>	46.5	47.8	<b>2.7%</b>	18.57	19.56	<b>5.1%</b>
<i>C<sub>eco</sub></i>	125.1	124.1		123.1	124.1		158.9	189.40		186	191.2		185.7	195.6	
<i>C<sub>ergo</sub></i>	90.1	87.4		73.2	87.4		27.6	3.90		0	0		0	0	
<b>Instance</b>															
<i>H</i>	161.9	155	<b>0.0%</b>	148.15	148.425	<b>0.2%</b>	132.5	129.95	<b>0.0%</b>	63.025	75.325	<b>16.3%</b>	27.9	40.11	<b>30.4%</b>
<i>C<sub>eco</sub></i>	161.9	155		161.3	156.8		168.4	224.30		252.1	245.8		279	392.1	
<i>C<sub>ergo</sub></i>	117.6	119.7		108.7	123.3		96.6	35.60		0	18.5		0	1	
<b>Instance</b>															
<i>H</i>	102.9	100.4	<b>0.0%</b>	94.6	91.65	<b>0.0%</b>	75.45	70.55	<b>0.0%</b>	37.45	37.475	<b>0.1%</b>	14.97	14.86	<b>0.0%</b>
<i>C<sub>eco</sub></i>	102.9	100.4		106	100.5		150.2	139.90		149.8	149.9		149.7	148.6	
<i>C<sub>ergo</sub></i>	61.6	75.7		60.4	65.1		0.7	1.20		0	0		0	0	
<b>Instance</b>															
<i>H</i>	134.5	132.8	<b>0.0%</b>	124.05	125.6	<b>1.2%</b>	101.6	104.30	<b>2.6%</b>	50.625	53.575	<b>5.5%</b>	20.48	21.43	<b>4.4%</b>
<i>C<sub>eco</sub></i>	134.5	132.8		134.4	132.8		201.7	191.40		198.6	214.3		204.8	214.3	
<i>C<sub>ergo</sub></i>	99.4	104		93	104		1.5	17.20		1.3	0		0	0	
<b>Instance</b>															
<i>H</i>	98.6	102.2	<b>3.5%</b>	90.775	97.9	<b>7.3%</b>	70.85	79.60	<b>11.0%</b>	35.1	40.8	<b>14.0%</b>	14.96	16.32	<b>8.3%</b>
<i>C<sub>eco</sub></i>	98.6	102.2		101.5	101.8		136.7	153.50		140.4	163.2		149.6	163.2	
<i>C<sub>ergo</sub></i>	71.6	88.1		58.6	86.2		5	5.70		0	0		0	0	

from Van Laarhoven and Aarts (1987).  $T$  is computed around some hundreds, and  $\beta \approx 0.999$ . Tested instances with all three collaboration modes only rarely achieved repetition of the best solution, nevertheless the range of the best three solutions was consistently below 1% of the target value, which is an acceptable value for real-life application considering natural fluctuation of the process execution. When tested with only two collaboration modes (without cooperation), similar range could be found, and best solution could be achieved multiple times by the algorithm in 45% of cases. Full results are visible in Table 4.

Overall results show little benefit of cooperation mode at low  $\alpha$  values, which is natural since this mode offers little time saving compared to manual and prevents parallelisation of tasks. However, for  $\alpha = 0.5$ , introduction of cooperation mode delivers better results, with an average improvement of 4% across the test instances, which brings significant benefit for economic and ergonomic trade-off. For greater  $\alpha$  values, cooperation also delivers improved results, which is also foreseeable result since ergonomic focus will lead to use collaborative robot as a ‘third hand’ across the whole process (see Figure 7).



**Figure 7.** Relative improvement brought by introduction of cooperation mode for various  $\alpha$  values.

**Table 5.** Summary results for real case study.

$\alpha$	0			0.25			0.5			0.75			0.9		
Modes	3	2	IR	3	2	IR	3	2	IR	3	2	IR	3	2	IR
Instance	Real case study														
$H'$	77.3	81.3	<b>4.9%</b>	66.8	75.6	<b>11.6%</b>	49.0	69.4	<b>29.4%</b>	24.7	44.7	<b>44.9%</b>	9.9	18.8	<b>47.4%</b>
$C_{eco}$	77.3	81.3		80.2	81.3		95.0	97.9		98.6	117.0		98.6	138.8	
$C_{ergo}$	49.6	67.8		26.5	53.8		3.0	30.9		0.0	16.5		0.0	2.9	

## 4.2. Application on real case study

Similar trend could be observed on real case study, with significantly higher benefit (up to 29.4% reduction for the objective function at  $\alpha = 0.5$ ), see Table 5.

Algorithm results for the real case study have been physically applied in a working environment (see Figure 8) for better grounded assessment of the proposed method. Video captures of several representative configurations can be found [here](#).<sup>2</sup> Several observations could be made on the relevance of the model and solution.

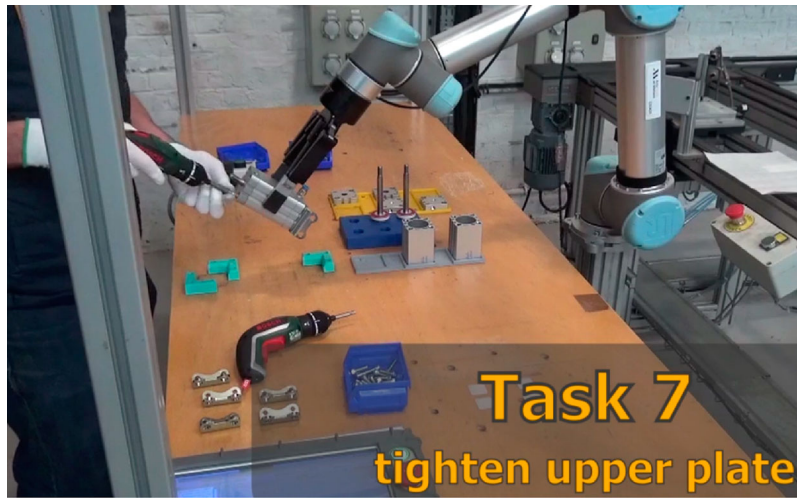
### 4.2.1. Handling of transitions between tasks

Throughout the implementation of proposed solutions, it has been necessary to add or modify several robot activation (through button pressing) to secure absence of unwanted interference between operator and cobot. Indeed, even though task times are deterministic, in practice operator pace may fluctuate. As long as this concerns a succession of manual tasks, this is little concern. But at the process points where interaction may happen between operator and robot – i.e. when there is an allocation change between two consecutive tasks, some measures have to be taken to avoid safety risk for the operator. As an example, if the operator is delayed on a manual task on a main piece, it must be secured that the robot will be waiting until this task is completed before

to execute its own next task if it involves interacting with the same piece, as this situation may lead to potential collision or trapping of operator hands. Likewise, in case of opposite switch from robot or cooperative task towards manual task, which may involve releasing a component or sub assembly from robot gripper, it is mandatory to wait until operator is ready to receive it.

Such situations may be handled through high level technological solution that can observe operator movement to anticipate the moment he or she will be ready to interact, which may not require any alteration in the process design. Nevertheless for real-life application with limited investment, simple and robust solutions have to be considered, where operator has to give positive confirmation of his readiness to move to the next step. Such confirmation action may have a noticeable effect on the obtained cycle time, since they are generally in the range of a second each. Such confirmation actions are comparable in appearance to the setup times, which are already studied in multiple balancing problems (Sternatz 2014; Vallada and Ruiz 2011; Rocha et al. 2008).

However, setup times are generally dependant on the sequence of tasks (necessity for tooling changeover for instance) and can be represented in a matrix form, where the value of the setup time can be found at the coordinates



**Figure 8.** Experimental setup for real case application (here using cooperation mode).

representing the two task numbers involved. In the studied case, those setup times, or rather transition times, are dependant on the respective allocations of the tasks involved: a transition has been added if at least one of the direct predecessors of the considered task has a different allocation than the task itself.

## 5. Conclusion and further works

In this paper, an assignment problem between different resources is studied. Several tasks are needed to make one product. There are precedence constraints between some of the tasks. The considered resources are an operator and a robot. A third allocation option is considered: both operator and robot are used at the same time to process the task (cooperation mode). The task time to process a task is different according to the mode: worker, robot or cooperation. In average, robot needs  $k$  more times than the worker to make the same activity. According to the mode, relaxation times are defined. Thus each task is defined by three process times and relaxation times. The objective of the considered problem is to assign all the tasks to resources, considering two objectives: economic and ergonomic performance. An approximate method has been developed to identify approximate solutions, highlighting some benefits in using concurrently several collaboration modes to balance ergonomic and economic performance. This method and tools maybe easily generalised towards other ergonomic models involving relaxation times. With concern for real-life application, the objective function and solving algorithm have incorporated cyclic production impact. Results on several test instances show significant performance leverage when both economic and ergonomic aspects are considered,

offering new possibilities for designing better quality collaborative process. Application on real case study could confirm the theoretical findings and also highlighted the need for modelling transition impact when different collaboration modes are being used on consecutive tasks. A specific study has been carried out on the minimisation of fatigue accumulated through cycles using PMES. Other ergonomic models can be tested, covering other aspects of ergonomic assessment, as force application, extreme joint position, or even awkward posture. As long as an ergonomic score can be associated to a given task, the algorithm developed in this paper may be used, providing the objective function is amended to reflect the requirement of the associated model.

Nevertheless, several limitations and potential extensions could be considered. Video recording methodology used in this study has limited accuracy and ability to capture whole body movement. Extension of this type of study into broader environment, as a workcell for instance, would benefit from technology like motion capture, as proposed by Daria et al. (2018). Moreover, the ergonomic risk has been assessed through a single operator, designing an improved solution that may not benefit equally from the changes implemented. The alleged reconfigurability of the collaborative robot could be studied further to develop processes custom solutions for operator of various age or presenting different anthropometric characteristics, as suggested by Calzavara et al. (2020) and Katirae et al. (2021). Furthermore, introducing changes to an existing process, using an algorithm based on a inevitably simplified model, may overlook several human aspects, which may undermine the resulting solution (Neumann et al. 2021). As a comprehensive strategy for implementation of



collaborative robots towards improved work condition and performance, human factors should also be considered as a key contribution.

## Notes

1. To trigger relaxation time in the presented case study, some component weights have been increased, within the capability range of the selected collaborative robot
2. <https://www.youtube.com/channel/UCTe59h3sT9fxOv6UBvzsnGg/videos>

## Data availability statement

The data that support the findings of this study are available from the corresponding author, AQ, upon reasonable request.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## References

- Aaltonen, Iina, Timo Salmi, and Ilari Marstio. 2018. "Refining Levels of Collaboration to Support the Design and Evaluation of Human-robot Interaction in the Manufacturing Industry." *Procedia CIRP* 72: 93–98.
- Battaia, Olga, and Alexandre Dolgui. 2013. "A Taxonomy of Line Balancing Problems and their Solution approaches." *International Journal of Production Economics* 142 (2): 259–277. Accessed 2020-10-26. <https://linkinghub.elsevier.com/retrieve/pii/S0925527312004616>.
- Battini, Daria, Martina Calzavara, Alena Otto, and Fabio Sgarbossa. 2017. "Preventing Ergonomic Risks with Integrated Planning on Assembly Line Balancing and Parts Feeding." *International Journal of Production Research* 55 (24): 7452–7472.
- Battini, Daria, Xavier Delorme, Alexandre Dolgui, Alessandro Persona, and Fabio Sgarbossa. 2016. "Ergonomics in

- Assembly Line Balancing Based on Energy Expenditure: a Multi-objective Model." *International Journal of Production Research* 54 (3): 824–845.
- Becker, Christian, and Armin Scholl. 2009. "Balancing Assembly Lines with Variable Parallel Workplaces: Problem Definition and Effective Solution Procedure." *European Journal of Operational Research* 199 (2): 359–374.
- Borba, Leonardo, and Marcus Ritt. 2014. "A Heuristic and a Branch-and-Bound Algorithm for the Assembly Line Worker Assignment and Balancing Problem." *Computers & Operations Research* 45: 87–96. Accessed 2020-10-26. <https://linkinghub.elsevier.com/retrieve/pii/S030505481300347X>.
- Boysen, Nils, Malte Fliedner, and Armin Scholl. 2007. "A Classification of Assembly Line Balancing Problems." *European Journal of Operational Research* 183 (2): 674–693.
- Calzavara, Martina, Daria Battini, David Bogataj, Fabio Sgarbossa, and Ilenia Zennaro. 2020. "Ageing Workforce Management in Manufacturing Systems: State of the Art and Future Research Agenda." *International Journal of Production Research* 58 (3): 729–747.
- Daria, Battini, Calzavara Martina, Persona Alessandro, Sgarbossa Fabio, Visentin Valentina, and Ilenia Zennaro. 2018. "Integrating Mocap System and Immersive Reality for Efficient Human-centred Workstation Design." *IFAC-Papers OnLine* 51 (11): 188–193.
- Elmaghraby, Salah Eldin. 1977. *Activity Networks: Project Planning and Control by Network Models*. New York: John Wiley & Sons.
- Faber, Marco, Jennifer Bützler, and Christopher M. Schlick. 2015. "Human-robot Cooperation in Future Production Systems: Analysis of Requirements for Designing an Ergonomic Work System." *Procedia Manufacturing* 3: 510–517.
- Fanjul-Peyro, Luis, and Rubén Ruiz. 2011. "Size-reduction Heuristics for the Unrelated Parallel Machines Scheduling Problem." *Computers and Operations Research* 38 (1): 301–309.
- Gjeldum, N., A. Aljinovic, M. Crnjac Zizic, and M. Mladineo. 2021. "Collaborative Robot Task Allocation on an Assembly Line Using the Decision Support System." *International Journal of Computer Integrated Manufacturing* 34: 1–17.
- Gourgand, Michel, Nathalie Grangeon, and Nathalie Klement. 2014. "An Analogy Between Bin Packing Problem and Permutation Problem: A New Encoding Scheme." In *Advances in Production Management Systems. Innovative and Knowledge-Based Production Management in a Global-Local World*, vol. 438, 572–579. Berlin, Heidelberg: Springer.
- Hartmann, Sönke, and Dirk Briskorn. 2010. "A Survey of Variants and Extensions of the Resource-constrained Project Scheduling Problem." *European Journal of Operational Research* 207 (1): 1–14.
- Herrmann, Jeffrey, Jean-Marie Proth, and Nathalie Sauer. 1997. "Heuristics for Unrelated Machine Scheduling with Precedence Constraints." *European Journal of Operational Research* 102 (3): 528–537.
- Katiraei, Niloofar, Martina Calzavara, Serena Finco, Daria Battini, and Olga Battaia. 2021. "Consideration of Workers' Differences in Production Systems Modelling and Design: State of the Art and Directions for Future Research." *International Journal of Production Research* 59 (11): 3237–3268.
- Kim, Dong-Won, Kyong-Hee Kim, Woosung Jang, and Chen F. Frank. 2002. "Unrelated Parallel Machine Scheduling with Setup Times Using Simulated Annealing." *Robotics and Computer-Integrated Manufacturing* 18 (3–4): 223–231.
- Klement, Nathalie, and Cristóvão Silva. 2020. "A Generic Decision Support Tool to Planning and Assignment Problems: Industrial Applications and Industry 4.0." In *Scheduling in Industry 4.0 and Cloud Manufacturing*, 167–192. Springer.
- Kolisch, Rainer, and Arno Sprecher. 1997. "PSPLIB—a Project Scheduling Problem Library: OR Software-ORSEP Operations Research Software Exchange Program." *European Journal of Operational Research* 96 (1): 205–216.
- Lin, Y. K., H. T. Hsieh, and F. Y. Hsieh. 2012. "Unrelated Parallel Machines Scheduling Problem Using An Ant Colony Optimization Approach." *International Journal of Industrial and Manufacturing Engineering* 6 (8): 1727–1732.
- Lin, Shih-Wei, and Kuo-Ching Ying. 2015. "A Multi-Point Simulated Annealing Heuristic for Solving Multiple Objective Unrelated Parallel Machine Scheduling Problems." *International Journal of Production Research* 53 (4): 1065–1076.
- Malik, Ali Ahmad, and Arne Bilberg. 2019. "Collaborative Robots in Assembly: A Practical Approach for Tasks Distribution." *52nd CIRP Conference on Manufacturing Systems* 81: 665–670.
- Matheson, Eloise, Riccardo Minto, Emanuele G. G. Zampieri, Maurizio Faccio, and Giulio Rosati. 2019. "Human-Robot Collaboration in Manufacturing Applications: A Review." *Robotics* 8 (4): 100.
- McAtamney, Lynn, and E. Nigel Corlett. 1993. "RULA: A Survey Method for the Investigation of Work-related Upper Limb Disorders." *Applied Ergonomics* 24 (2): 91–99.
- Miralles, Cristobal, Jose Pedro Garcia-Sabater, Carlos Andres, and Manuel Cardoso. 2007. "Advantages of Assembly Lines in Sheltered Work Centres for Disabled. A Case Study." *International Journal of Production Economics* 110 (1–2): 187–197.
- Moreira, Mayron César O., Jean-François Cordeau, Alysson M. Costa, and Gilbert Laporte. 2015. "Robust Assembly Line Balancing with Heterogeneous Workers." *Computers & Industrial Engineering* 88: 254–263. Accessed 2020-10-26. <https://linkinghub.elsevier.com/retrieve/pii/S0360835215003058>.
- Moreira, Mayron César O., Marcus Ritt, Alysson M. Costa, and Antonio A. Chaves. 2012. "Simple Heuristics for the Assembly Line Worker Assignment and Balancing Problem." *Journal of Heuristics* 18 (3): 505–524. Accessed 2020-10-26. <http://link.springer.com/10.1007/s10732-012-9195-5>.
- Neumann, W. Patrick, Sven Winkelhaus, Eric H. Grosse, and Christoph H. Glock. 2021. "Industry 4.0 and the Human Factor—A Systems Framework and Analysis Methodology for Successful Development." *International Journal of Production Economics* 233: 107992.
- Nikabadi, Mohsen Shafiei, and Reihaneh Naderi. 2016. "A Hybrid Algorithm for Unrelated Parallel Machines Scheduling." *International Journal of Industrial Engineering Computations* 7: 681–702.
- Otto, Alena, and Armin Scholl. 2011. "Incorporating Ergonomic Risks into Assembly Line Balancing." *European Journal of Operational Research* 212 (2): 277–286. Accessed 2020-10-26. <https://linkinghub.elsevier.com/retrieve/pii/S037722171100110X>.
- Pearce, Margaret, Bilge Mutlu, Julie Shah, and Robert Radwin. 2018. "Optimizing Makespan and Ergonomics in Integrating

- Collaborative Robots into Manufacturing Processes.” *IEEE Transactions on Automation Science and Engineering* 15 (4): 1772–1784.
- Pfund, Michele, John W. Fowler, and Jatinder N. D. Gupta. 2004. “A Survey of Algorithms for Single and Multi-objective Unrelated Parallel-machine Deterministic Scheduling Problems.” *Journal of the Chinese Institute of Industrial Engineers* 21 (3): 230–241.
- Pini, Fabio, Francesco Leali, and Matteo Ansaloni. 2015. “A Systematic Approach to the Engineering Design of a HRC Workcell for Bio-Medical Product Assembly.” In *2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA)*, 1–8. IEEE.
- Quenehen, Anthony, Jérôme Pocachard, and Nathalie Klement. 2019. “Process Optimisation Using Collaborative Robots-Comparative Case Study.” *IFAC-PapersOnLine* 52 (13): 60–65.
- Quenehen, Anthony, Stephane Thiery, Nathalie Klement, Lionel Roucoules, and Olivier Gibaru. 2020. “Assembly Process Design: Performance Evaluation Under Ergonomics Consideration Using Several Robot Collaboration Modes.” In *IFIP International Conference on Advances in Production Management Systems*, 477–484. Springer.
- Rocha, Pedro Leite, Martín Gómez Ravetti, Geraldo Robson Mateus, and Panos M. Pardalos. 2008. “Exact Algorithms for a Scheduling Problem with Unrelated Parallel Machines and Sequence and Machine-Dependent Setup Times.” *Computers and Operations Research* 35 (4): 1250–1264.
- Rubinovitz, Jacob, Joseph Bukchin, and Ehud Lenz. 1993. “RALB – A Heuristic Algorithm for Design and Balancing of Robotic Assembly Lines.” *CIRP Annals* 42 (1): 497–500.
- Simões, Ana Correia, Ana Pinto, Joana Santos, Sofia Pinheiro, and David Romero. 2022. “Designing Human-Robot Collaboration (HRC) Workspaces in Industrial Settings: A Systemic Literature Review.” *Journal of Manufacturing Systems* 62: 28–43.
- Sternatz, Johannes. 2014. “Enhanced Multi-Hoffmann Heuristic for Efficiently Solving Real-world Assembly Line Balancing Problems in Automotive Industry.” 235 (3): 740–754. Accessed 2020-10-26. <https://linkinghub.elsevier.com/retrieve/pii/S0377221713009041>.
- Thiemermann, Stefan. 2005. *Direkte Mensch-Roboter-Kooperation in der Kleinteilemontage mit einem SCARA-Roboter*. PhD thesis.
- Tsarouchi, Panagiota, Alexandros-Stereos Matthaikiakis, Sotiris Makris, and George Chryssolouris. 2017. “On a Human-Robot Collaboration in An Assembly Cell.” *International Journal of Computer Integrated Manufacturing* 30 (6): 580–589.
- Vallada, Eva, and Rubén Ruiz. 2011. “A Genetic Algorithm for the Unrelated Parallel Machine Scheduling Problem with Sequence Dependent Setup Times.” *European Journal of Operational Research* 211 (3): 612–622.
- Van Laarhoven, Peter J. M., and Emile H. L. Aarts. 1987. “Simulated Annealing.” In *Simulated annealing: Theory and applications*, 7–15. Springer.
- Van Peteghem, Vincent, and Mario Vanhoucke. 2010. “A Genetic Algorithm for the Preemptive and Non-Preemptive Multi-Mode Resource-Constrained Project Scheduling Problem.” *European Journal of Operational Research* 201 (2): 409–418.
- Wang, Haibo, and Alidaee Bahram. 2019. “Effective Heuristic for Large-Scale Unrelated Parallel Machines Scheduling Problems.” *Omega* 83: 261–274.
- Wang, Shijin, and Benyan Ye. 2019. “Exact Methods for Order Acceptance and Scheduling on Unrelated Parallel Machines.” *Computers and Operations Research* 104: 159–173.
- Weckenborg, Christian, and Thomas S. Spengler. 2019. “Assembly Line Balancing with Collaborative Robots Under Consideration of Ergonomics: A Cost-Oriented Approach.” *IFAC-PapersOnLine* 52 (13): 1860–1865.
- Yang, Bibo, Joseph Geunes, and William J. O’Brien. 2001. *Resource-Constrained Project Scheduling: Past Work and New Directions*. Technical Report. Department of Industrial and Systems Engineering, University of Florida.