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A tri-objective model for the manual assembly line design integrating economic, technical and ergonomic aspects

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Abstract: Smart assembly lines are a milestone of Industry 4.0 allowing the efficient and effective production of complex products with an acceptable time-to-market. According to the literature and the standard practice, these lines are made of a set of equipped stations with a worker for each of them. Products flow the stations in sequence to perform their assembly cycle. Nowadays, the best design of assembly lines deals with the joint inclusion and best mix of multiple dimensions, often in conflict and requiring good trade-off solutions. This paper proposes and preliminary applies a tri-objective linear programming model to design a single-model smart assembly line aiming at optimizing the system annual equivalent cost, the time balance among the stations and, finally, the level of fatigue each worker is exposed. Details on the model boundaries are given together with its full mathematical formulation and linearization, to reduce its complexity. Finally, a preliminary case study links the model to practice showing its feasibility and potential benefit for the modern smart industries.

Keywords: smart assembly, manual assembly line, tri-objective model, line balancing, worker fatigue, assembly, modeling of manufacturing operations, modeling of assembly units.

1. INTRODUCTION AND LITERATURE REVIEW

Assembly represents a crucial production process. Assembly of goods accounts for more than 50% of the total production time and 20% of the total production cost. In the modern changeable industrial environment, assembly systems need to be able to adapt to products, market, technologies and regulatory requirements (ElMaraghy and ElMaraghy, 2016; Bortolini et al., 2018). Within the assembly system design, the assembly line balancing problem (ALBP) is a widespread decision problem, which significantly impacts on the performance and the productivity of the line (Fathi et al., 2019). The ALBP aims at the best assignment of the assembly tasks among the assembly stations optimizing one or more, often conflicting, objectives without violating technological and operational constraints. The literature usually classifies ALBPs into two main groups: simple assembly line balancing problems (SALBPs) and generalized assembly line balancing problems (GALBPs) (Pereira and Alvarez-Miranda, 2018). SALBPs can be divided into two sub-groups: SALBP-1 and SALBP-2. The former aims at minimizing the number of stations knowing the cycle time, the latter aims at minimizing the cycle time, knowing the number of workstations. GALBPs include more practical considerations and constraints from the real world, e.g. U-shaped assembly lines, variable task times and zoning constraints (Bautista et al., 2016). Another relevant classification of the ALBP is done according to the production mix the assembly systems are able to produce. In such a way, ALBPs can be grouped into single- and mixed-model product types: the former deals with the production of a single homogeneous model, the latter deals with a multi-model production. The literature on ALBP modelling is wide. Among the most relevant and recent contributions, Akpinar and Baykasoglu (2014) defined a mixed-integer linear optimization model for the mixed-model ALBP considering setups between the tasks of the same model and setups due to model switches, parallel workstation, zoning constraints and sequence dependant setup times between tasks. Kucukkoc and Zhang (2015) faced the parallel two-sided ALBP as an emerging paradigm able to efficiently produce large sized products joining the benefits of both parallel assembly lines and two-sided assembly lines. The Authors defined a mathematical model minimizing two conflicting objectives, i.e. the cycle time and the number of workstations, and use the ant colony meta-heuristic method in the solving procedure. Results proved that the simultaneous minimization of the two objectives helped to increase the assembly system efficiency. Roshani and Nezami (2017) explored the ALBP with multi-manned workstations where multiple workers simultaneously perform different tasks on the same product. The Authors developed a model to minimize the number of workers and the number of workstations, solved adopting a simulated annealing algorithm. Rabbani et al. (2016) faced the robotic mixed-model assembly line balancing with the goal to minimize the robot purchasing and setup costs, the sequence dependant setup costs and the cycle time. The proposed model tried to determine an optimal or sub-optimal configuration of tasks and workstations in U-shaped assembly line balancing. Alavidoost et al. (2016) proposed a novel bi-objective mixed-integer linear programming model considering, as conflicting

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objective functions, the minimization of the number of stations and of the cycle time. Results showed that the proposed model may constitute a valid framework able to assist the decision makers to manage uncertainty in assembly line problems.

Although most of the existing contributions focus on optimizing temporal and economic aspects, a parallel stream attempts to introduce ergonomic issues in the classical ALBP. In fact, ergonomics plays a crucial role in the manufacturing and assembly environments because of the need to guarantee a safe and comfortable workspace for the human operators minimizing discomfort, stress and fatigue (Botti et al., 2017; Bortolini et al., 2020). In this field, Otto and Scholl (2011) proposed heuristic approaches to introduce multiple ergonomic indices in the classical ALBP. By means of such approaches, the Authors proved the feasibility to achieve a wide reduction of the ergonomic risks of workplaces at low computational costs even without increasing the number of workstations. Moreover, the proposed methodology allowed for a controllable increase of the manufacturing capacity best managing the trade-off between increased costs from adding stations and reduced ergonomic risks. Kara et al. (2014) introduced a mathematical model to integrate ergonomics and resource restrictions into ALBP. The proposed model is cost-based under psychological and physical strain, worker skills, multiple workers, equipment, working postures and illumination level restrictions. Battini et al. (2016) defined a novel multi-objective model for solving the ALBP including ergonomic aspects. According to the main features of the assembly workstations, the energy expenditure concept was used to estimate the ergonomic level by using the Predetermined Motion Energy System technique, which helps to rapidly estimate the energy expenditure values within the working activities. Bortolini et al. (2017) proposed a multi-objective optimization model for the ALBP to assign the assembly tasks to the workstations distinguishing the assembly activities involved in task execution and component picking. The aim was the simultaneous minimization of the assembly line takt time and of the ergonomic risk, in terms of REBA index, which evaluates the risk of musculoskeletal disorders of more than 600 working postures determined by the combination of trunk, neck, legs, upper arms, lower arms and wrists postures. Results proved that the final assembly line balancing configuration was characterized by remarkable performances for both takt time and ergonomic risk objective functions. Zhang et al. (2020) formulated a U-shaped assembly line worker assignment and balancing problem to simultaneously minimize the cycle time and the ergonomic risks. Global results suggested that the proposed multi-objective algorithm outperformed existing methods on a large number of benchmark instances.

The literature review analysis shows the need for integrated approaches simultaneously considering time, economic and ergonomic issues in the classic ALBP. According to this scenario, this paper faces the SALBP-1 proposing and applying a tri-objective linear programming model to design a single-model smart manual assembly line aiming at optimizing the system annual equivalent cost, the time balance among the assembly workstations and, finally, the level of fatigue each worker is exposed. About the last point, while existing papers focus on specific ergonomic indices, e.g. postural indices, repetitive actions indices, etc., in this paper a fully-flexible fatigue indicator is introduced in the model formulation, able to integrate all the traditional and specific ergonomic indicators.

According to this background, the remainder of this paper is organized as follows. Section 2 states the problem and introduces the tri-objective linear programming model for the SALBP-1. Section 3 applies the model to an industrial case study and discusses the main results. Finally, Section 4 concludes the paper with final remarks and future research opportunities.

2. PROBLEM DESCRIPTION, ASSUMPTIONS AND NOTATIONS

The aim of this section is to introduce and describe the tri-objective mathematical optimization model for the SALBP-1. In the proposed scenario, an assembly system composed by a set of workstations is considered where each worker is assigned to a specific workstation. Relevant and widespread goals of the assembly line balancing are the minimization of the costs as well as the best balance of the working times of the assembly workstations. Besides these traditional objectives, an ergonomic objective function is included in the model formulation, which balances the physical efforts to which the operators of the assembly workstations are exposed. In fact, each operation requires a specific physical effort and the assignment of "high-fatigue" tasks to a limited number of operators could compromise their production performances throughout the working day. Such performance reduction could inevitably lead to the formation of bottlenecks, with significant implications on the productivity of the whole system. To include and best manage this relevant aspect, in the model formulation each assembly task is associated to a specific level of fatigue and an upper fatigue limit for each worker is considered, depending by its specific features, e.g. age, physical conditions, etc. In this way, this model overcomes the use of specific ergonomic indicators, e.g. postures indicators, repetitive actions indicators, etc., promoting the use of a fully-flexible general index.

In the model formulation, the following notations are introduced.

Sets

$i, i' = 1, \dots, m$	Sets for assembly workers
$j, j' = 1, \dots, n$	Sets for assembly tasks

Parameters

C	Equivalent annual fix cost of each station, for tools and equipment [€/year]
E_i	equivalent annual cost for worker i [€/year]
f_j	task fatigue for task j [pt]
F	upper fatigue limit for standard worker [pt]

P_j	set of transitive predecessors of task j
T_c	cycle time [s]
t_{ij}	task time for task j and worker i [s]
ξ_i	fatigue coefficient for worker i [%]

Decisional variables

x_{ij}	1 if task j is assigned to worker i, 0 otherwise
z_i	1 if operator i is used, 0 otherwise
$\tau_{ii'}$	Auxiliary variable
$\varphi_{ii'}$	Auxiliary variable

Objective functions

$min\Psi^C$	Assembly line equivalent annual cost
$min\Psi^B$	Assembly line time balancing
$min\Psi^F$	Workers fatigue balancing

2.1 Optimization model formulation

The first objective function minimizes the assembly line equivalent annual cost. Such value consists of a fixed cost for each station and of a variable cost, which depends on the assigned operators. The analytic formulation is as follows.

$$\Psi^C = \sum_{i=1}^{m} (C + E_i) \cdot z_i \qquad (1)$$

The second objective function is for the assembly line time balancing, i.e. it minimizes the difference between the working times of each station. The non-linear analytic formulation is in (2), while the final linear objective function is in (3) by using the auxiliary variable $\tau_{ii'}$ and introducing the additional constraint in (10).

$$\Psi^B = \sum_{i=1:z_i=1}^{m-1} \sum_{i'=i+1:z_{i'}=1}^{m} \left| \sum_{j=1}^{n} t_{ij} \cdot x_{ij} - \sum_{j=1}^{n} t_{i'j} \cdot x_{i'j} \right| \qquad (2)$$

$$\Psi^B_{lin} = \sum_{i=1}^{m-1} \sum_{i'=i+1}^{m} \tau_{ii'} \qquad (3)$$

The third objective function is for the workers fatigue balancing, i.e. it minimizes the difference between the global level of fatigue related to the tasks performed by the operators in each station. The non-linear analytic formulation is in (4), while the final linear objective function is in (5) by using the auxiliary variable $\varphi_{ii'}$ and introducing the additional constraint in (11).

$$\Psi^F = \sum_{i=1:z_i=1}^{m-1} \sum_{i'=i+1:z_{i'}=1}^{m} \left| \frac{1}{\xi_i} \cdot \sum_{j=1}^{n} f_j \cdot x_{ij} - \frac{1}{\xi_{i'}} \cdot \sum_{j=1}^{n} f_j \cdot x_{i'j} \right| \qquad (4)$$

$$\Psi^F_{lin} = \sum_{i=1}^{m-1} \sum_{i'=i+1}^{m} \varphi_{ii'} \qquad (5)$$

Moreover, the model is subject to the following feasibility constraints.

$$\sum_{i=1}^{m} x_{ij} = 1 \qquad \forall\, j \qquad (6)$$

$$\sum_{j=1}^{n} t_{ij} \cdot x_{ij} \le T_c \cdot z_i \qquad \forall\, i \qquad (7)$$

$$\sum_{i=1}^{m} i \cdot x_{ij'} \le \sum_{i=1}^{m} i \cdot x_{ij} \qquad \forall\, j, j' \in P_j \qquad (8)$$

$$\sum_{j=1}^{n} f_j \cdot x_{ij} \le F \cdot \xi_i \cdot z_i \qquad \forall\, i \qquad (9)$$

$$\tau_{ii'} \ge \sum_{j=1}^{n} t_{ij} \cdot x_{ij} - \sum_{j=1}^{n} t_{i'j} \cdot x_{i'j} - BIG_M \cdot (2 - z_i - z_{i'}) \qquad \forall\, i, i' > i \qquad (10)$$

$$\varphi_{ii'} \ge \frac{1}{\xi_i} \cdot \sum_{j=1}^{n} f_j \cdot x_{ij} - \frac{1}{\xi_{i'}} \cdot \sum_{j=1}^{n} f_j \cdot x_{i'j} - BIG_M \cdot (2 - z_i - z_{i'}) \qquad \forall\, i, i' > i \qquad (11)$$

$$x_{ij}, z_i \text{ binary} \qquad \forall\, i, j \qquad (12)$$

$$\tau_{ii'} \ge 0 \;\; \varphi_{ii'} \ge 0 \qquad \forall\, i, i' > i \qquad (13)$$

Equation (6) ensures each task is assigned to one worker. (7) guarantees per each worker not to exceed the available cycle time to perform the assembly tasks. (8) sets the precedence constraints between tasks. (9) ensures that the overall level of fatigue associated to each worker does not exceed its maximum limit. Equations (10) and (11) allow the linearization of the assembly line time balancing and workers fatigue balancing objective functions. Finally, (12) and (13) set the domains of the decisional variables.

The industrial scenario adopted to apply the proposed tri-objective model is described in next Section 3.

3. INDUSTRIAL CASE STUDY

The proposed tri-objective model is applied to a numeric case study representative of an operative industrial context. The instance considers the assembly of one product requiring the execution of 22 assembly tasks by up to 15 human operators. The cycle time T_c is 540 seconds (productivity equal to 6.67 pcs/h). The precedence graph for the considered product is in Fig. 1.

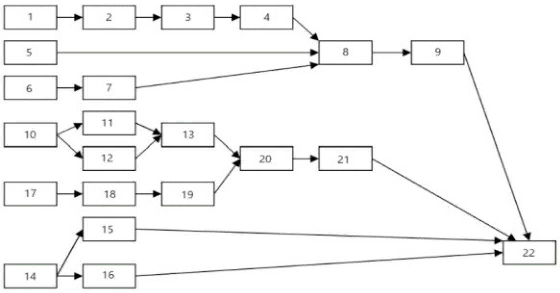

Fig. 1. Precedence graph for the considered product.

The equivalent annual fix cost of each station (parameter C) is $25000 \frac{€}{year}$ while the equivalent annual cost for each worker is Table 1.

Table 1. Equivalent annual cost for workers *i*

i	E_i [€/year]
1	28000
2	29000
3	29000
4	29500
5	31000
6	32000
7	32000
8	33000
9	33400
10	35000
11	38000
12	35700
13	39000
14	41300
15	42000

Data about task time for task j and worker i (t_{ij}) and the task fatigue for task j (f_j) are in Appendix A. Finally, the upper fatigue limit for a standard worker (parameter F) is set to a value of 100 pt while ξ_i is 100% for all the workers, i.e. they are supposed to be in optimal physical conditions.

Globally, the set of input data leads to 795 decisional variables and 711 constraints. The model is coded in AMPL language and processed adopting the solver Gurobi Optimizer© v.4.0.1.0 on an Intel® Core^{TM} i7 CPU @ 2.40GHz and 8.0GB RAM workstation. The solving method to build the Pareto frontier is the Normalized Normal Constraint Method (NNCM) presented by Messac et al. (2003). In detail, two Pareto frontiers are built and evaluated: the cost vs time balance and the cost vs fatigue balance. The cost element is maintained in all the two frontiers because it represents the primary goal of every industrial company. Starting from these data, 11 points per Pareto frontier are computed. The solving time is approximately of about 2 minutes per point. The key results are described in the following sub-section 3.1.

3.1 Results and discussion

Fig. 2 and Fig. 3 respectively present the annual cost vs time balancing and annual cost vs fatigue balancing Pareto frontiers obtained by applying the NNCM method. In the figures, the non-dominated points are shown, only.

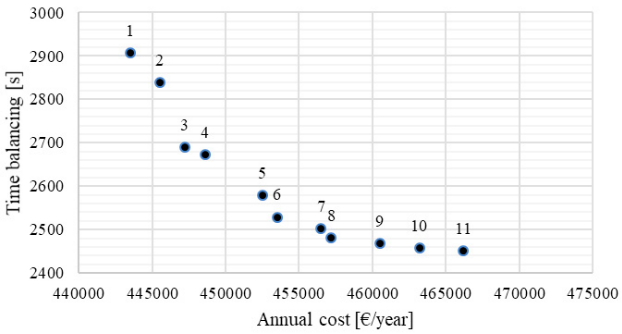

Fig. 2. Time balancing vs annual cost Pareto frontier.

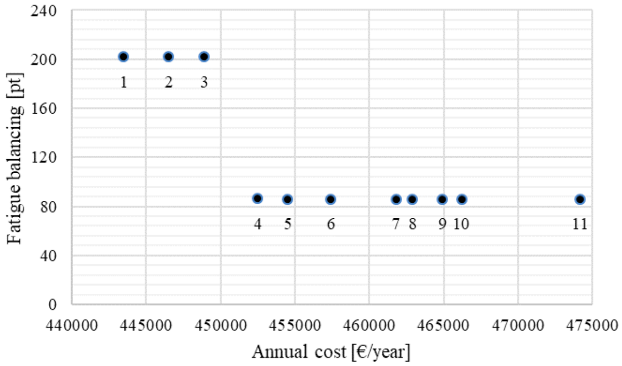

Fig. 3. Fatigue balancing vs annual cost Pareto frontier.

The Pareto frontier trends show the existence of a good balance between the conflicting objectives, as demonstrated by the values of the three anchor points (Fig. 4).

In all the anchor point configurations, 8 assembly stations are opened, with one operator per station. In detail, listing the operators from 1 to 15, in the annual cost optimum the selected workers are: 1, 2, 3, 4, 5, 6, 7 and 8. In the time balance optimum the selected workers are: 1, 3, 4, 5, 6, 12, 14 and 15, while in the fatigue balance optimum the selected workers are: 1, 2, 4, 6, 9, 13, 14 and 15.

Obj. Function	Annual cost [€/year]
Annual cost opt.	443500
Time balance opt.	466200
Fatigue balance opt.	474200

	Worker up time [s]							
Obj. Function	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
Annual cost opt.	135	98	526	116	188	48	176	527
Time balance opt.	149	216	207	194	202	208	210	480
Fatigue balance opt.	231	150	144	97	227	241	214	531

	Worker fatigue [pt]							
Obj. Function	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
Annual cost opt.	98	100	86	100	93	52	86	65
Time balance opt.	100	80	94	97	97	65	82	65
Fatigue balance opt.	87	86	84	90	83	85	82	83

Fig. 4. Anchor point values.

3.2 *Proposed final solution*

Among the non-dominated points, the choice of the final assembly configuration structure is according to any suitable informal approach. In this study, the final point is selected among those characterizing the time balancing vs annual cost Pareto frontier, according to the criteria of the minimum Euclidean distance from the Utopia point, i.e. the point with time balance and cost optima as coordinates, appropriately modified. In detail, in the proposed final configuration, the selected workers are: 1, 2, 3, 4, 5, 7, 8 and 15. Other relevant information, e.g. worker and task assignment to the stations, worker up time and fatigue trend, are in next Table 2 and Fig. 5.

Table 2. Data about the proposed final configuration

Station	Worker	Tasks assigned	Worker up time [s]	Worker fatigue [pt]
1	1	5,6	107	80
2	2	7,14	220	80
3	3	10,12,15,16	211	94
4	4	11,13,17	194	97
5	5	18,19,20,21	208	97
6	7	1,2,3	259	85
7	8	4,8	224	82
8	15	9,22	480	65

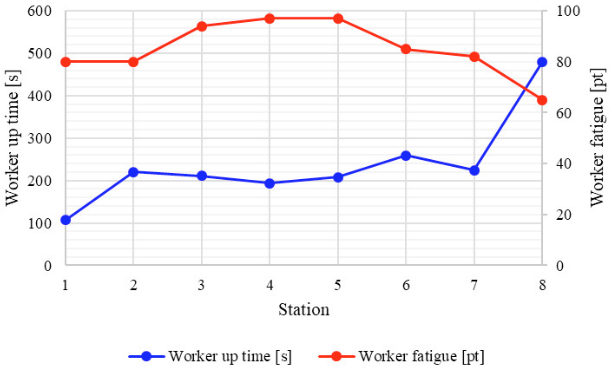

Fig. 5. Worker up time and fatigue trend in each station.

Analysing the task-station assignment and the worker up time and fatigue trend, it has to be noted that Station 1 is characterized by a low value of worker up time and by a high value of fatigue. On the other hand, tasks assigned to Station 8 lead to a high value of worker up time but to a low value of fatigue. To compensate and balance such stations, job rotation approaches can be introduced switching periodically the operators from one station to the other and vice-versa.

In the selected point, the annual equivalent cost is equal to $453500\ \frac{€}{\text{year}}$ (increase of the annual cost optimum of 2.25%). Moreover, assuming a number of working days per year equal to 220 and shifts of $8\ \frac{\text{h}}{\text{days}}$, the annual productivity is equal to $11740\ \frac{\text{pcs}}{\text{year}}$ getting an unitary cost equal to $38.63\ \frac{€}{\text{pc}}$ (increase of the unitary cost optimum of 2.25%).

4. CONCLUSIONS AND FUTURE RESEARCH

In the assembly system design, the assembly line balancing problem (ALBP) is a widespread decision problem, usually addressed in terms of time and economic performance optimization. However, in the emerging Industry 4.0 era, a multi-objective perspective, able to optimize multiple conflicting objectives, is needed and highly expected. Following this stream, this paper proposes and applies a tri-objective linear programming model to design a single-model smart manual assembly line aiming at optimizing the system annual equivalent cost, the time balance among the stations and, finally, the level of fatigue each worker is exposed. Results prove the existence of a significant trade-off between the objective functions. The final selected assembly configuration allow achieving good performances in terms of time and fatigue balance with a small increase of the annual cost (+2.25%). Among the future research activities, the application of the model to larger real instances is of interest.

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Appendix A.

Table A.2. Task time for task *j* and worker *i*

t_{ij} [s]	1	2	3	4	5	6	7	8	9	10	11
1	42	25	197	190	68	39	72	50	33	52	40
2	37	24	204	192	63	37	70	51	31	55	40
3	41	28	201	187	70	36	68	49	32	50	38
4	36	23	200	189	64	31	66	47	33	49	38
5	36	27	198	194	65	32	70	46	33	49	39
6	39	29	200	185	60	35	67	48	34	49	37
7	34	26	199	183	63	36	69	49	29	47	37
8	35	24	191	180	61	30	66	44	27	45	34
9	40	30	194	180	61	31	66	45	29	44	34
10	35	25	191	184	61	30	66	45	27	45	34
11	34	22	190	177	57	28	66	41	24	45	34
12	33	22	186	178	56	23	61	40	23	40	30
13	30	21	181	169	60	27	60	41	21	40	31
14	28	21	183	175	58	23	62	39	23	38	28
15	29	20	177	176	58	25	60	38	20	37	27

t_{ij} [s]	12	13	14	15	16	17	18	19	20	21	22
1	35	120	153	65	65	39	23	64	41	89	525
2	34	118	150	65	65	40	24	62	41	89	525
3	35	115	148	63	63	38	23	63	41	89	515
4	34	117	148	62	62	39	21	61	40	86	515
5	34	118	147	59	59	37	22	61	39	86	515
6	32	112	146	59	59	36	20	58	38	86	505
7	31	113	143	59	59	36	19	57	38	81	505
8	29	110	140	58	58	35	19	57	38	81	500
9	28	110	140	58	58	35	18	56	36	81	498
10	29	108	138	55	55	34	17	54	34	79	490
11	26	107	137	55	55	34	17	53	33	78	490
12	25	102	134	55	55	31	15	52	34	77	480
13	25	101	131	52	52	32	14	52	32	75	480
14	24	99	129	52	52	30	14	49	32	75	460
15	25	99	126	51	51	28	14	48	30	74	460

Table A.2. Task fatigue for task *j*

j	f_j [pt]
1	20
2	40
3	25
4	30
5	50
6	30
7	60
8	52
9	35
10	41
11	40
12	20
13	20
14	20
15	15
16	18
17	37
18	11
19	23
20	42
21	21
22	30