**Abstract**

***3.1 Research assumptions***

Given the nature of this study, no hypothesis was presented and tested. However, the assumptions taken in this study are stated as follows:

* The number of activities needed to be performed on the product is already specified.
* The operational sequence of each activity is specified.
* The production rate and machine speed are different for various activities.
* The number of constituting cells is specified.
* The cell layout is S-shaped but cells are arranged linearly in two rows in the developed model. Besides, the machines are placed linearly in a single row.
* The distance between the candidate positions of machine placement in each cell is pre-calculated and specified.
* The minimum and the maximum numbers of machines in each cell are specified.
* There is only one of each type of machine.
* Operations performed sequentially by parts.
* All parts are available for processing at zero moments.
* When an operation is initiated on a machine, it is not preempted until it is completed.

***3.2. Mathematical modeling***

A mathematical model is developed to address the research problem. First, the indices, parameters, and decision variables are defined. Afterward, the objective functions and the model constraints are detailed.

*3.2.1 Indices*

|  |  |
| --- | --- |
| A set of subassembly activities |  |
| Workstations |  |
| Process control stations |  |
| Product |  |
| Time cycle |  |
| Skills needed in each workstation |  |
| Machinery |  |
| Part manufacturing cells |  |
| Locations of part manufacturing cells |  |
| Subassemblies or subassembly manufacturing cells |  |
| Locations of subassembly manufacturing cells |  |
| Location of subassembly activities |  |
| Final precedence and secondary assembly activities |  |
| Locations of final assembly activities |  |

***3.2.2 Parameters***

|  |  |
| --- | --- |
| The maximum number of (manufacturing and control) workstations |  |
| Number of operators |  |
| Number of orders placed for product *o* |  |
| Predetermined cycle time |  |
| Total available time for the manufacturing process |  |
| The ideal time for completing the manufacturing process at workstation *r* |  |
| Demand for product o in cycle |  |
| Activity time for product o |  |
| Number of fixed staff with skill *SK* |  |
| Number of fixed staff with skill *SK* in cycle "" |  |
| The staff training cost |  |
| The number of temporary staff employed in cycle "" |  |
| The number of permanent staff employed in cycle "" |  |
| The overtime rate of temporary staff employed in cycle "" |  |
| The overtime rate of permanent staff employed in cycle "" |  |
| Total working hours in each cycle |  |
| The maximum shipment cost affordable by the organization |  |
| The average procurement time for product o at workstation r |  |
| The number of required parts for manufacturing each unit of product o |  |
| Procurement time from workstation “r” to control station "" |  |
| The distance between workstation “r” to control station "" |  |
| The cost between workstation “r” to control station "" per unit |  |
| Transportation speed between two workstations |  |
| The ideal weighted time for manufacturing the final product |  |
| Transfer time for transporting product o from workstation “r” to control station "" |  |
| Activity time of job "" for product o |  |
| The manufacturing time of product o |  |
| Transportation time between station “r” to station "r + 1" |  |
| Total lead time for assembly |  |
| The wage of permanent staff in regular hours |  |
| The wage of temporary staff in regular hours |  |
| The wage of permanent staff in overtime hours |  |
| The wage of temporary staff in overtime hours |  |
| The maximum amount of product o that can be transported each time from workstation “r” to the process control station "" |  |
| The total cost of transferring between manufacturing cell “*Ce”* and the subassembly manufacturing cell “s” per distance unit |  |
| The distance between the location of part manufacturing cell “”and the entrance of the subassembly manufacturing cell “q” if the u-shaped subassembly line at location “q” is oriented clockwise |  |
| The total shipment cost between the subassembly manufacturing cell “s” and activity “" on the final assembly line |  |
| The distance between the exit of subassembly manufacturing cell “q” and the location of final assembly activity “fa” if the u-shaped subassembly line at location “q” is oriented clockwise |  |
| The total shipment cost between activities () in the subassembly manufacturing cell per distance unit |  |
| The distance between the locations of subassembly activity “fa” |  |
| The distance between the location of part manufacturing cell “”and the entrance of subassembly manufacturing cell “q” if the u-shaped subassembly line at location “q” is oriented counterclockwise |  |
| The distance between the exit of subassembly manufacturing cell “q” and the location of final assembly activity “fa” if the u-shaped subassembly line at location “q” is oriented counterclockwise |  |
| The total cost of shipment between the manufacturing cell “*”*and the subassembly manufacturing cell “s” per distance unit |  |
| Total number of the required subassemblies “s” |  |
| The total shipment cost between “” activities in the subassembly manufacturing cell “s” per distance unit |  |
| The shipment cost of each subassembly class in manufacturing process “s” in moving inside the subassembly manufacturing cells after performing a “” activity per distance unit |  |
| The total shipment cost between “” activities in the subassembly manufacturing cell “s” per distance unit |  |
| The size of the subassembly class during the manufacturing process "s" in moving inside the subassembly manufacturing cells after performing a “” activity |  |
| The total shipment cost between the subassembly manufacturing cell “s” and activity “”on the final assembly line |  |
| The shipment cost of each subassembly class “s” in moving between the subassembly manufacturing cell “s” and the activity locations of the final assembly per distance unit |  |
| Utilization factor of the “s” subassembly in the “o” model |  |
| The existing demand for the “o” model |  |
| The size of subassembly class “s” in transferring between the subassembly manufacturing cell “s” and locations of final assembly activities |  |
| Shipment cost of each model class during manufacturing product “o” in transferring between the locations of the final assembly line activities after performing the “” activity per distance unit |  |
| A fraction of the model for manufacturing product “o” that requires “” activity immediately after “” activity |  |
| Job security factor based on skill “SK” |  |
| The inflation rate |  |
| Job hardship factor based on skill “SK” |  |

***3.2.3 Decision variables***

|  |  |
| --- | --- |
| The binary variable; if the “” activity is assigned to workstation “r”, it will be equal to 1 otherwise 0 |  |
| The binary variable; if workstation “r” is used for the assembly process, it will be equal to 1, otherwise 0 |  |
| The binary variable; if workstation “r” is used for the manufacturing process control station, it will be equal to 1, otherwise 0 |  |
| The binary variable; if the “r” manufacturing process control station serves the “” manufacturing process control station, it will be equal to 1, otherwise 0 |  |
| Total overtime duration of temporary workers at workstation “r” during the “” cycle |  |
| Total overtime duration of permanent workers at workstation “r” during the “” cycle |  |
| Binary variable; if the operator with skill “SK” is assigned to workstation “r” in the “” cycle, it will be equal to 1, otherwise 0 |  |
| Binary variable; if the operator with skill “SK” is assigned during the overtime duration to workstation “r” in the “” cycle, it will be equal to 1, otherwise 0 |  |
| Binary variable; if the operator with skill “SK” can operate in workstation “r”, it will be equal to 1, otherwise 0 |  |
| If there is a flow between the “r” and “” workstations, the binary variable will be equal to 1, otherwise 0. |  |
| The maximum completion time of activities |  |
| The amount of product/sub-product “o” that can be carried in each shipment from “r” to “” workstation |  |
| The weighting factor of the first section of the first objective function |  |
| The weighting factor of the second section of the first objective function |  |
| The weighting factor of the third section of the first objective function |  |
| If the part manufacturing cell “”is assigned to the “” location, it will be equal to 1, otherwise 0 |  |
| If the subassembly manufacturing cell “s” is assigned to “q” location, it will be equal to 1, otherwise 0. |  |
| If the U-shaped assembly line is oriented clockwise in the “s” sub-assembly manufacturing cell, it will be equal to 1, otherwise 0. |  |
| Binary variable; If the assembly activity “” is assigned to the “fa” location to manufacture final product models, it will be equal to 1, otherwise 0. |  |
| Binary variable; If the assembly activity “” is assigned to the “fa” location to manufacture final product models, it will be equal to 1, otherwise 0. |  |

***3.3 Objective functions***

|  |  |
| --- | --- |
|  | (1) |
|  | (2) |
|  | (3) |
|  | (4) |

Eq. (1) shows the first objective function that aims to minimize the time cycle in the stations, the ideal weighted time, and balance the production/assembly line. Eq. (2) aims to minimize the workforce cost that encompasses the cost of working in regular and overtime hours, and the cost of staff training. Besides, the third objective function focuses on minimizing the shipment cost between two workstations. The first part minimizes the shipment cost from the part manufacturing unit to the subassembly manufacturing unit. Moreover, the second part focuses on minimizing the shipment cost of the subassemblies from the subassembly manufacturing cells to the final assembly line. Finally, the third part minimizes the shipment cost between the locations of assembly activities in the final assembly line. On the other hand, workforce satisfaction is maximized in the fourth objective function by optimizing job security and hardship factors. The inflation rate is present in the first (positive) component of this objective function as increasing the inflation rate reduces the unemployment rate and thus will benefit the workforce. Additionally, it has been attempted to reduce the job hardship in the second component of this objective function, while maintaining its negative sign.

***3.4. Constraints***

|  |  |
| --- | --- |
|  | (5) |
|  | (6) |
|  | (7) |
|  | (8) |
|  | (9) |
|  | (10) |
|  | (11) |
|  | (12) |
|  | (13) |
|  | (14) |
|  | (15) |
|  | (16) |
|  | (17) |
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|  | (19) |
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|  | (21) |
|  | (22) |
|  | (23) |
|  | (24) |
|  | (25) |
|  | (26) |
|  | (27) |
|  | (28) |
|  | (29) |
|  | (30) |

Constraint (5) guarantees that each station carries out only one activity. In other words, two activities will not be simultaneously defined for a machine to avoid any overlap. Constraint (6) ensures that the manufacturing time of each product does not exceed the cycle time. Furthermore, Constraint (7) specifies that the number of manufacturing and process control workstations does not exceed the number of permissible workstations available. Moreover, Constraint (8) ensures that the duration of activity “”at workstation “r” does not exceed the ideal time cycle set for workstation “r”. Additionally, constraints (9) and (10) assign only a worker to each workstation and prevent assigning excessive additional labor force to each machine. Constraint (11) guarantees the fact that the required number of workers is supplied in each cycle and no machine is left without an operator. Constraint (12) specifies that the required time for manufacturing each product is the sum of time cycles required for completing activities performed in the manufacturing process. Constraint (13) ensures that the total time that a worker spends on a machine for manufacturing a product is at least equal to the time required for manufacturing that product based on that product demand (assures that the time required for manufacturing a product according to its demanded quantity). Constraint (14) ensures that at least once in each time cycle the required skill SK (in regular or overtime hours) is assigned to the machine requiring that skill. Otherwise, the activity will not require that skill to be completed. Constraint (15) states that the number of works allocated during regular and overtime hours is equal to the total number of operators so that there is no shortage of manpower at any time. Constraint (16) specifies the maximum intra-station shipment cost that is affordable by the organization.

Constraint (17) specifies that shipment time between two workstations on the distance between them divided by the operating and shipment speed. Furthermore, Constraint (18) assures that the procurement lead time for manufacturing of product *o* at workstation “*r*” is equal to the product of the number of similar parts required for manufacturing the product and the time needed to prepare or manufacture each part. Moreover, Constraint (19) demonstrates that the lead time for manufacturing a product is obtained as the sum of manufacturing, procurement, and inter-station shipment times.

Constraint (20) specifies that the time needed to transport a product from one workstation to another does not exceed the cycle time. Furthermore, Constraint (21) guarantees that the activity and transportation times do not exceed the cycle time. Constraint (22) shows that the time required for completing activity “” for product o is maximally equal to the cycle time. Constraint (23) specifies the number of operators has and Constraint (24) keeps the time needed to do activity “” in workstation “r” maximally equal to the weighted ideal time. Constraint (25) ensures that in the case of selecting a workstation, an activity can be assigned to it; otherwise, no activity shall be assigned to an unselected workstation. Constraints (26) and (27) calculate the total shipment cost between two specific machines per distance unit. Ultimately, constraints (28) to (30) specify the upper and lower bounds of the skill-based job security factor, the skill-based job hardship factor, and the inflation rate, respectively. Accordingly, the job security factor and inflation rate can never be equal to zero.

**4. Solving the model**

In the present study, the data recorded in the operational checklists of the production system of Pars Khodro Company were used to implement the proposed model and find practical solutions. The NSGA-II genetic algorithms and MATLAB R2019a software were employed for solving the model and analyzing the data through the following steps:

Step 1: Generating the initial population based on scale and problem constraints

Step 2: Evaluating the generated population in terms of the defined objective functions

**Figure 1.** The schematic view of the second step

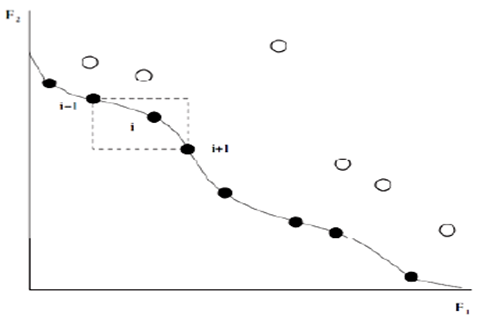
Step 3: Applying the non-dominated sorting algorithm

The members of the population are sorted into groups so that the members in the first group are considered an entirely non-dominated group by other members of the current population. Similarly, the members of the second group are only dominated by those in the first group but are not dominated by members of other groups. This process is similarly repeated in other groups until all members of each group are assigned a rank based on their group number.

**Figure 2.** The schematic view of the third step

Step 4:Calculating the crowding distance as a control parameter

This parameter is calculated for each member of each group. It specifies a proximity measure of the member to other group members. A high value of this parameter results in divergence and represents a better distribution of members of the population:

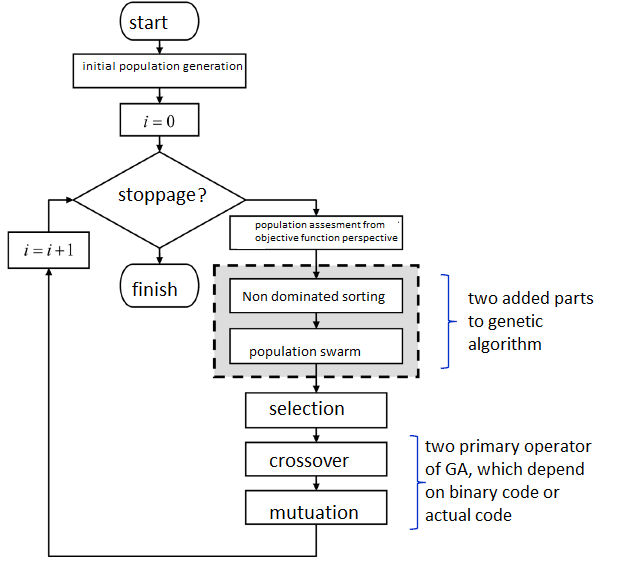


**Figure 3.** Calculation of a control parameter called crowding distance (Deb et al., 2000)

Step 5: Choosing the parent population for reproduction

One of the selection mechanisms is to run a double-elimination tournament among two randomly selected members of the population.

Step 6: Performing mutations and crossovers



**Figure 4.** Performance of NSGA-II algorithm (Kalianmoi Deb, 2000)

**Table 1.** Factors and candidate levels in the algorithm (NSGA-II)

|  |  |  |  |
| --- | --- | --- | --- |
| High | Medium | Low | Algorithm parameters |
| 45 | 30 | 15 | Number of Population |
| 0.9 | 0.7 | 0.5 | Crossover percent |
| 0.4 | 0.3 | 0.2 | Mutation percent |

According to Taguchi orthogonal arrays, L9 was selected as an appropriate experimental design for adjusting the proposed parameters. L9 array is an experimental design with 9 experiments. The experimental designs for the proposed algorithm are presented in Table 2.

**Table 2.** Experimental design with L9 orthogonal array for NSGA-II algorithm

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Solution values | Algorithm parameters | | | Order |
| MID | **Pm** | **Pc** | **nPop** |
| 6.9517 | 1 | 1 | 1 | 1 |
| 37.162 | 2 | 2 | 1 | 2 |
| 3.0812 | 3 | 3 | 1 | 3 |
| 9.465 | 2 | 1 | 2 | 4 |
| 5.6565 | 3 | 2 | 2 | 5 |
| 9.5747 | 1 | 3 | 2 | 6 |
| 16.3752 | 3 | 1 | 3 | 7 |
| 14.2128 | 1 | 2 | 3 | 8 |
| 7.9231 | 2 | 3 | 3 | 9 |

The proposed meta-heuristic algorithm is implemented for each Taguchi experiment. Afterward, the average ratios (S/N) estimated for each level of the related factors in the algorithm are displayed in Figure 5. Moreover, the optimal levels of input parameters for the algorithm are presented in Table 3.



**Figure 5.** S/N diagram of NSGA-II algorithm parameters

The multi-objective mathematical model developed for the flexible job-shop problem (FJSP) in the automotive company was solved. The results are presented in the following section. Given the complexity of the model in terms of the number of variables, constraints, and data, the model was developed as a state-space model (SSM) in MATLAB software. To solve this optimization model, a non-dominated sorting genetic algorithm was used in MATLAB software. After solving the problem, the outputs are represented as follows. The initial input values of the model parameters are shown in Table 3.

**Table 3.** Values of input indices

|  |  |  |
| --- | --- | --- |
| Item | Index (set) | Vlaue |
| 1 | Sub-assembly activities set | 8 |
| 2 | Work stations | 4 |
| 3 | Process control stations | 6 |
| 4 | Product | 4 |
| 5 | Time period | 10 |
| 6 | Categorization of the required capabilities for each workstation | {1,2,3}, {3,4,5}, {6,7,8}, {2,4,6}, {3,4,8}, {4,5,7} |
| 7 | Machinery | 10 |
| 8 | Parts production cells | 5 |
| 9 | Locations of parts production cell | 5 |
| 10 | Sub-assemblies or sub-assemblies production cells | 10 |
| 11 | Locations of sub-assembly production cell | 10 |
| 12 | Sub-assembly activity location | 8 |
| 13 | Prerequisites and successor final assembly activities | 8 |
| 14 | Locations of final assembly activities | 6 |

**Table 4.** Binary decision variables

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Variable | Period | | | | | | | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|  | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
|  | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
|  | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
|  | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
|  | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
|  | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
|  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|  | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
|  | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
|  | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
|  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|  | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
|  | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |

Table 4 shows the results of the assignment of manufacturing activities to each of the workstations and assembly stations. As can be observed, each activity that is being assigned to a workstation for the manufacturing process is not simultaneously under control or assembly process. This confirms the adherence to the sequence of manufacturing activities through the flexible job-shop operations. Furthermore, the data in Table 4 confirm that the inspection process can be performed simultaneously during the manufacturing process to reduce the time taken to manufacture the product(s) in the production cycle. The fifth and sixth rows in Table 4 show the assignment of skilled operators to the manufacturing and inspection activities. As can be seen, a skilled operator equipped has been assigned to correctly perform the production cycle of the product(s) in the required time cycles. However, an expert has been only assigned the second to fifth cycles for the random inspection process.

**Table 5.** non-negative decision variables

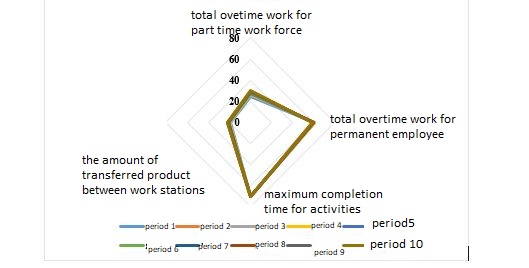
|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Variable | Period | | | | | | | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|  | 25 | 27 | 26 | 26 | 27 | 28 | 29 | 29 | 29 | 30 |
|  | 61 | 61 | 61 | 61 | 60 | 60 | 60 | 60 | 59 | 59 |
|  | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
|  | 19 | 20 | 20 | 20 | 21 | 21 | 21 | 22 | 22 | 22 |
|  | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
|  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|  | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |

The results of the analysis of the non-negative decision variables in the problem are demonstrated in Table 5. These decision variables include the total overtime (hour) of temporary and permanent workers at workstation “r” in cycle “”, the maximum completion time of activities (hour), and the quantity of transported product o from workstation “r” to workstation “ŕ”. As was expected and shown in Table 5, the overtime time (hour) of the temporary workers is approximately half of that of permanent workers in all time cycles. However, the completion time of the activities in all time cycles is identical and equal to 70 hours. This shows that temporary and permanent operators attempt to complete manufacturing processes at a similar standard time by assisting each other.

Table 6 shows the promotion level of the workers’ technical and professional skills. For instance, when the skills of 12 workers in cycle 1 and site 3 promote from level 2 to level 3 and the skills of 2 workers in site 1 and cycle 2 develop from level 3 to level 5, the workers’ skills and expertise can be promoted to raise their productivity and flexibility, instead of employing new workers and firing them in future cycles.

**Table 6.** the enhancement of technical and specialized skill levels of staff

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Level enhancement | Work station | Period | | | | | | | | | |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| 2 → 5 | 2 |  |  |  |  | 5 |  |  |  |  |  |
| 3 → 5 | 2 |  |  |  | 8 |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
| 2 → 3 | 2 |  |  |  |  |  |  |  |  |  | 1 |
| 2 → 3 | 3 | 12 |  |  |  |  |  |  |  |  |  |
| 3 → 5 | 1 |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
| 2 → 3 | 3 | 12 |  |  |  |  |  |  |  |  |  |
| 2 → 4 | 1 |  | 1 |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
| 1 → 3 | 3 | 3 |  |  |  |  |  |  |  |  |  |
| 2 → 3 | 3 | 12 |  |  |  |  |  |  |  |  |  |

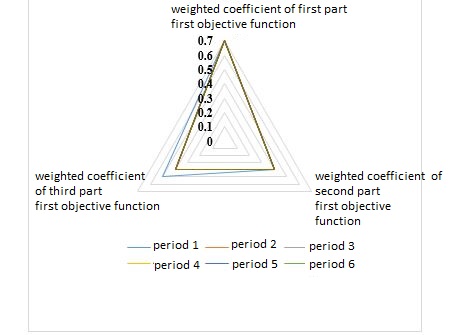


**Figure 6.** Integer non-negative variables diagram

The empty cells in Table 7 show zero value, indicating that the final products have not been delivered to the consumers in the same ordering cycle. Additionally, the first column shows the product type, the second column indicates the active stations for each product, and the third column shows the manufacturing process which can be completed either during regular (1) and overtime hours (2). For example, the number of type-5 products manufactured on site 2 and cycle 5 is equal to 170 in regular working hours. On the other hand, the number of type-2 products outsourced on the identical site and cycle is equal to 367.

**Table 7.** Production planning resulted from the proposed model’s solution

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Products | Stations | Production type | Period | | | | | | | | | |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| 1 | 1 | 1 | 195 | 359 | 308 |  |  |  |  |  |  |  |
| 2 | 1 | 205 | 821 | 750 | 653 | 330 | 435 | 200 |  |  |  |
| 3 | 2 | 232 |  | 496 | 590 | 120 | 320 | 263 |  |  |  |
| 2 | 1 | 1 | 905 | 1137 | 656 | 994 |  | 223 | 200 | 584 |  | 903 |
| 2 | 1 | 458 | 194 | 212 | 561 | 680 | 540 | 860 | 920 |  |  |
| 3 | 1 |  |  |  | 40 | 570 | 307 |  | 936 | 670 | 560 |
| 3 | 1 | 1 | 295 | 235 | 249 |  |  | 120 | 100 | 100 | 530 | 327 |
| 2 | 1 | 200 | 970 | 768 | 830 | 160 | 90 |  | 300 | 620 | 593 |
| 3 | 1 | 396 |  | 102 | 780 | 250 |  |  |  |  |  |
| 4 | 1 | 1 | 482 | 283 | 729 | 407 |  | 130 | 237 | 353 |  |  |
| 2 | 2 | 767 | 518 | 655 | 626 | 930 | 280 | 427 | 387 | 833 |  |
| 3 | 2 |  |  |  | 226 | 200 |  |  | 107 |  |  |
| 5 | 1 | 1 | 742 | 1090 | 717 | 1047 | 991 | 753 | 483 | 183 | 353 | 370 |
| 2 | 1 |  |  | 230 |  | 170 |  |  | 277 |  |  |
| 3 | 1 | 399 | 58 |  | 731 | 367 | 164 | 320 | 665 |  |  |



**Figure 7.** Radar diagram of weighted coefficients of the first objective function

Considering the weighting coefficients for the three parts of the first objective function and also the data for different time cycles presented in Table 5, Figure 7 displays the radar chart of these coefficients. According to this chart, the weighting coefficient of the first part of the first objective function is greater than the corresponding coefficients in the other two parts.

**Table 8.** Values of objective functions

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Objective function | Period | | | | | | | | | |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Final production time (hours) | 667 | 646 | 639 | 633 | 629 | 621 | 618 | 615 | 611 | 609 |
| Labor force cost (million) | 62 | 58 | 55 | 53 | 50 | 47 | 45 | 44 | 43 | 42 |
| Cost of transfer between two workstations (millions) | 226 | 217 | 215 | 213 | 211 | 202 | 200 | 199 | 198 | 197 |
| Workforce satisfaction (%) | 0.3 | 0.32 | 0.37 | 0.39 | 0.4 | 0.41 | 0.45 | 0.61 | 0.62 | 0.67 |

Table 8 shows the numerical values of each of the four objective functions in the time cycles in question. As can be seen, as the inter-station shipment and workforce costs decrease, the labor costs from the first to the tenth cycles decrease from 62 million to 42 million monetary units. Furthermore, by decreasing the labor costs, the final production time will be reduced. Accordingly, by professionalizing the activities of each workstation and decreasing inter-station shipment and labor forces, worker satisfaction increases through optimization of job security and hardship factors as shown in Table 9.

**Table 9.** Computational results of NSGA-II algorithm comparison criteria

| Rep. number | S | NPS | | Time | MID | D |
| --- | --- | --- | --- | --- | --- | --- |
| 1  2  3  4  5  6  7  8  9  10 | 1.3014  1.5123  1.2139  1.6387  1.1349  0.9097  0.8844  1.3248  0.9566  0.9818 | 8  6  17  6  11  10  8  5  7  11 | 36.7234  101.8156  123.5392  202.9154  448.7538  788.9973  1093.6903  1494.4092  1767.4664  1905.4221 | | 36.7667  1.4804  1.2348  1.1824  1.0643  1.0375  1.0341  1.0307  1.0160  1.0112 | 1937.3412  2823.0652  5696.6991  3490.7567  6027.9463  7554.5423  4855.6296  5591.4897  5910.7505  7338.3404 |

Table 9 displays the estimation of the Pareto-based multi-objective validation criteria for the research problem. As the distance from the ideal solution, the relative distance between consecutive solutions, the algorithm solution time decrease, the selected metaheuristic (NSGA-II) algorithm has a more efficient performance. Moreover, as the diameter of the special cube diameter in the final objective values for the set of non-dominated solutions and the number of Pareto optimal solutions increases, the solution algorithm performs more efficiently. The data presented in Table 9 for 10 iterations confirm the optimal performance of the solution algorithm.