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doi:10.15199/48.2021.01.17

Method of electrical equipment assembly rescheduling for assembly lines without intermediate buffers

***Abstract**. The method presented herein is used to build new schedules, particularly when it is necessary to modify previous schedules for assembly operations. It is used to include new, urgent orders in a schedule, as well as if at least one machine malfunctions. This method applies to assembly of electrical equipment in a one-way assembly line without parallel machines and without local storages. Due to lack of intermediate buffers in the assembly line setup, two cases were taken into account: possibility of the machines being blocked by products awaiting further operations and no-wait scheduling. The assembly schedules concerning these cases were compared by conducting computational experiments. These experiments were conducted on constructed integer programming task models.*

***Streszczenie.** Przedstawiona metoda służy do budowy nowych harmonogramów, zwłaszcza gdy jest konieczne dokonanie zmian w uprzednich uszeregowaniach operacji montażowych. Jest ona stosowana w celu uwzględnienia w harmonogramie nowych, pilnych zleceń, a także w przypadku awarii co najmniej jednej maszyny. Metoda dotyczy montażu sprzętu elektrycznego w jednokierunkowej linii montażowej bez maszyn równoległych oraz bez lokalnych magazynów. W związku z brakiem buforów międzyoperacyjnych w konfiguracji linii montażowej uwzględniono dwa przypadki: możliwość blokowania maszyn przez produkty oczekujące na wykonanie kolejnych operacji oraz szeregowanie „bez czekania". Harmonogramy montażu dotyczące tych przypadków zostały porównane za pomocą przeprowadzonych eksperymentów obliczeniowych. Eksperymenty te przeprowadzono na zbudowanych modelach zadań programowania całkowitoliczbowego. (**Metoda reharmonogramowania montażu sprzętu elektrycznego dla linii montażowych bez buforów międzyoperacyjnych**).*

Słowa kluczowe: harmonogramowanie montażu, reharmonogramowanie, szeregowanie operacji, szeregowanie bez czekania, programowanie całkowitoliczbowe,
Keywords: assembly scheduling, rescheduling, no-wait scheduling, integer programming.

Introduction

Assembly operation schedule for electrical equipment has a significant impact on the assembly costs of such equipment. Variable conditions of the assembly process (e.g. machine malfunctions) or acceptance of new, urgent orders may necessitate a modification of the performed assembly schedule. The issues concerning disturbances of the original schedule are described in detail in papers [1] and [2].

The method of modifying existing schedules described herein concerns the aforesaid cases. Creation of new schedules, that is rescheduling, includes operations performed in accordance with the original schedule, as well as those concerning new orders for assembly of electrical equipment.

Rescheduling, which is a special case of scheduling, is characterized by simultaneous distribution of operations in space and time [3]. Assembly scheduling involves single- or multi-level concepts. In the case of single-level concepts, there is a simultaneous allocation of operations to machines and determination of starting times for individual operations. In the alternative concept, these tasks are performed consecutively. The method proposed in this study is based on the single-level concept, also referred to as monolithic.

The developed scheduling method concerns operational planning, also known as operational control. The issues concerning scheduling are described in detail in studies [4] and [5]. Study [5] demonstrates that a substantial part of the applied scheduling methods is intended for building the shortest possible schedules. The developed assembly scheduling method utilizes a different optimality criterion, as the total costs of the assembly process are minimized. Obviously, the shorter the schedule, the lower the costs of the assembly process. According to the authors of study [6], optimization should be performed at various stages of the production process. The developed method concerns optimization of the production resources consumption.

The methods of determining new schedules are usually dedicated to specific configurations of the machinery. A description of various assembly line configurations, as well as scheduling methods for these configurations can be found in study [4]. The scheduling method described further on concerns assembly lines without intermediate buffers and without parallel machines. Due to lack of local storages where the products could wait for subsequent operations, two cases were taken into account. The first one is no-wait scheduling. This type of organizing the flow of products along a production line is characterized by the fact that the interruptions between operations on various machines regarding the same products are intended solely for transporting the product between the machines [7]. The developed method also utilizes an alternative concept, according to which the machines may also act as buffers.

The assembly line this method concerns is characterized by flexibility. Various types of flexibility were taken into account. One of them is the flexibility of the machines, which are capable of performing various types of assembly operations. This flexible assembly line can assemble various types of products at the same time, which means taking into account the flexibility of the production range. The route flexibility is also essential, as it enables performance of a given type of operations on different machines.

The mathematical tool applied in the developed method is mathematical programming. Linear mathematical models of integer programming tasks were built and used to determine the electrical equipment assembly schedules. The advantages of mathematical programming in scheduling are emphasized, e.g., in studies [4] and [9].

The assembly line rescheduling makes use of optimum or approximate methods. The schedules fixed using approximate methods are determined in a relatively short time, yet at the expense of a certain deviation from the optimal solution. The rudiments of creating approximate algorithms and the issues regarding construction of approximate algorithms were described, e.g., by Gonzales [10]. The developed method is an optimum one. Optimum solutions were determined e.g. using integer programming and monolithic approach. The use of mathematical programming and monolithic approach in the developed method was inspired, e.g., with works [4] and [5]. These works show very good perspectives for using mathematical programming in production planning and in assembly planning. This is the result of the observed development of software and computer technology. A review of mathematical problems connected with planning in production systems is presented in the study [13].

A detailed description of the characterized rescheduling method for electrical equipment assembly can be found in the next section. The following section presents the results of computational experiments used to verify this method.

Idea and mathematical description of the method

A unidirectional assembly line without intermediate buffers is given, such as, e.g., the line shown in fig. 1.

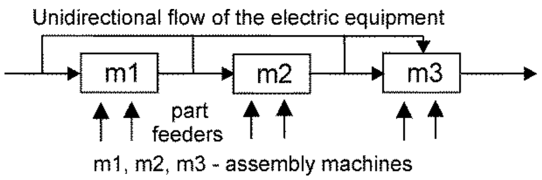

Figure 1. Example of diagram of assembly line without buffers

The described assembly line is used for simultaneous assembly of various types of products, namely electrical equipment. Some of the products are assembled in accordance with the original, pre-built schedule. For the remaining products, a new allocation of operations to machines is made, and the starting times for individual assembly operations are determined. It is also necessary to determine such assembly schedules for electrical equipment the use of which is the least costly. When building these schedules, alternative assembly routes must be considered. Thus, operations of the given time can be performed on different machines.

A block diagram of a one-level method intended for solving the aforesaid problem can be found in fig. 2.

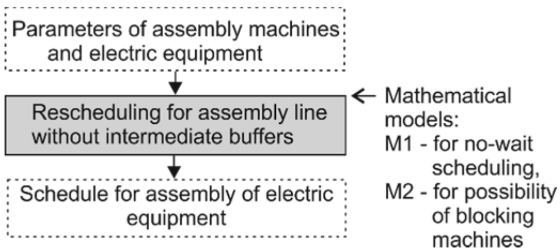

Figure 2. Block diagram of the method of rescheduling for assembly line without intermediate buffers

As seen in the block diagram in fig. 2, the problem was solved using mathematical programming. Two models if integer programming tasks were built:

- Model M1 concerning no-wait scheduling. In this case, the machines may not act as buffers, and the intervals between operations concerning the given product are used solely for transporting this product between various machines.
- Model M2, where the machines can be blocked by products awaiting consecutive operations. This means that a machine may act as a buffer.

Designations of indexes, sets, parameters and other variables used in the mathematical models M1 and M2 can be found in table 1.

Table 1. Notation: mathematical models

Basic sets:		
I	–	the set of machines; $I = \{1, \ldots, M\}$;
J	–	the set of operations; $J = \{1, \ldots, N\}$;
K	–	the set of types of products; $K = \{1, \ldots, W\}$;
K^1	–	the set of products which are to be assembly in accordance with the original schedule, $K^1 \subset K$,
K^2	–	the set of products which are to be assembly in accordance with the new schedule, $K^2 \subset K$;
L	–	the set of periods; $L = \{1, \ldots, H\}$;
Others sets:		
D	–	the set of pairs (k, j), in which the assembly operation $j \in J$ is required for type of product $k \in K^2$
F	–	the set of four elements (i, j, k, l), in which in accordance with the original schedule, $i \in I$, $j \in J$, $k \in K^2$, $l \in L$;
I_j	–	the set of the machines capable of performing operation j;
J^C	–	the set of tasks which require using the part feeder, $J^C \subset J$;
P	–	the set of pairs (k, j) in which the assembly operation $j \in J$ is the last operation of product $k \in K^2$;
R	–	the set of three elements (k, r, j), in which operation $j \in J_k$ is performed immediately before task $j \in J_k$, and $k \in K$;
Parameters:		
a_{ij}	–	working space required for operation j at machine i;
b_i	–	total working space of the assembly machine i;
c_k^1	–	cost incurred in a unit of time, resulting from delayed product assemblage, $k \in K^2$;
c_k^2	–	cost incurred in a unit of time, resulting from premature product assemblage, $k \in K^2$;
c_k^3	–	cost equal to the fine for failure to meet the latest, permissible deadline for product completion, $k \in K^2$;
c_{il}^4	–	cost of machine i operating during the period l;
$g_{\tau i}$	–	transport time between machines τ and i;
n_{il}	=	1, if machine i is available during period l, otherwise $n_{il} = 0$;
p_{jk}	–	assembly time for operation j of product $k \in K^2$;
u_k	–	assembly system readiness for performing operation concerning the product $k \in K^2$;
t_k^1	–	ordered completion time for product $k \in K^2$, subject to rescheduling;
t_k^2	–	the latest deadline for completing the product $k \in K^2$, after which a unit fine is charged;
Variables:		
x_{ij}	=	1, if type of assembly operation j is assigned to machine i, otherwise $x_{ij} = 0$;
q_{ijkl}	=	1, if product k is assigned to machine i to perform assembly operation j in period l, otherwise $q_{ijkl} = 0$;
z_k	–	time of completing assembly of the product $k \in K^2$
e_k^1	–	time of delay in assembling the product $k \in K^2$;
e_k^2	–	time concerning premature assemblage of the product $k \in K^2$; $e_k^2 = t_k^1 - z_k$;
w_k	=	1, if the latest deadline for assemblage the product $k \in K^2$ was exceeded, otherwise $w_k = 0$;
		For the M2 model only:
s_{ik}	–	time of starting operation j on machine i;
u_{ik}	–	time of ending operation j on machine i;
y_{ikl}	=	1 if machine i is blocked during period l by product k, otherwise $y_{ikl} = 0$;

The mathematical models M1 and M2:

(1) Minimize:
$$c_k^1 e_k^1 + c_k^2 e_k^2 + c_k^3 w_k + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{l\in L} c_{il}^4 q_{ijkl}$$

(2) Subject to: $\sum_{i\in I}\sum_{l\in L:n_{il}=1} q_{ijkl} = p_{jk}; (k,j)\in D;$

(3) $q_{ijkl} = 1;\ (i,j,k,l)\in F;$

(4) $q_{ijkl} \le x_{ij};\ i\in I; j\in J; k\in K; l\in L;$

(5) $\sum_{j\in J^c} a_{ij}x_{ij} \le b_i;\ i\in I;$

(6) $x_{ij} = 0;\ i\notin I_j; j\in J;$

(7) $\sum_{i\in I}\sum_{j\in J:(k,j)\in D} q_{ijkl} \le 1;\ k\in K^2;\ \ l\in L;$

(8) $\sum_{j\in J}\sum_{k\in K} q_{ijkl} \le n_{il};\ i\in I;\ \ l\in L;$

(9) $q_{ijkl} + q_{\tau jkf} \le 1;\ i,\tau\in I;\ \tau\ne i;\ (k,j)\in D; l,f\in L;$

(10) $lq_{ijkl} \ge u_k + (1-q_{ijkl}) \le 1;\ i\in I;\ \ (k,j)\in D; l\in L;$

(11) $\sum_{i\in I}\sum_{l\in L}\frac{q_{ijkl}}{p_{jk}} - \sum_{i\in I}\sum_{l\in L}\frac{q_{irkf}}{p_{rk}} - \frac{p_{jk}+p_{rk}}{2} \ge 0\ ; (k,r,j)\in R$

(12) $iq_{ijkl} \ge \tau q_{\tau rkf} - (H+1)(1-q_{ijkl});\ i,\tau\in I;$
$$(k,r,j)\in R;\ f,l\in L$$

(13) $lq_{ijkl} - fq_{\tau rkf} - 1 \ge g_{\tau i} - (H+1)(1-q_{ijkl});$
$$\tau,i\in I;\ \tau<i;\ (k,r,j)\in R;\ l,f\in L;\ f<l;$$

(14) $z_k = \sum_{i\in I}\sum_{l\in L}\frac{lq_{ijkl}}{p_{jk}} + \frac{p_{jk}-1}{2};\ (k,j)\in D;\ p_{jk}>0$

(15) $e_k^1 \ge z_k - t_k^1;\ k\in K^2$

(16) $e_k^2 \ge t_k^1 - z_k;\ k\in K^2$

(17) $z_k - t_k^2 \le (H+1)w_k;\ k\in K^2$

(18) $x_{ij}, q_{ijkl}\in\{0,1\};\ i\in I; j\in J; k\in K; l\in L;$

(19) $e_k^1, e_k^2, w_k, z_k \ge 0;\ k\in K^2$

For the M1 model only:

(20) $lq_{ijkl} - fq_{\tau rkf} - 1 \le g_{\tau i} + \sum_{m\in L:f<m<l}(q_{ijkm} + q_{\tau rkm}) +$
$$+(H+1)(1-q_{\tau rkf});\ (k,r,j)\in R; l,f\in L;\ f<l;\ \tau,i\in I;$$

For the M2 model only:

(21) $lq_{ijkl} - fq_{\tau rkf} - 1 \le \sum_{m\in L:f<m<l}(q_{ijkm} + q_{\tau rkm}) +$
$$+(H+1)(1-q_{\tau rkf}) + (H+1)(1-q_{irkf});\ (k,r,j)\in R;$$
$$l,f\in L;\ f<l;\ \tau,i\in I;$$

(22) $s_{ik} \le lq_{ijkl} + (H+1)(1-q_{ijkl});$
$$i\in I;\ j\in J;\ k\in K;\ l\in L;$$

(23) $u_{ik} \ge lxq_{ijkl} - (H+1)(1-xq_{ijkl});$
$$i\in I;\ j\in J;\ k\in K;\ l\in L;$$

(24) $lq_{ijkl} - fq_{\tau rkf} - 1 \le g_{\tau i} + \sum_{m\in L:f<m<l}(q_{ijkm} + q_{\tau rkm}) + \sum_{m\in L} y_{\tau km} + (H+1)(1-q_{\tau rkf});$
$$(k,r,j)\in R;\ \tau,i\in I;\ \tau\ne i;\ l,f\in L; f<l;$$

(25) $ly_{\tau kl} \le s_{ik} - g_{\tau i} - 1 + (H+1)(1-y_{\tau kl});$
$$\tau,i\in I;\ \tau<i;\ ; k\in K;\ l\in L;$$

(26) $ly_{ikl} \ge u_{ik} + 1 - (H+1)(1-y_{ikl});$
$$i\in I;\ i<M;\ k\in K;\ l\in L;$$

(27) $\sum_{k\in K}(q_{ijkl} + y_{ikl}) \le n_{il};\ i\in I;\ j\in J;\ l\in L;$

(28) $y_{ikl}\in\{0,1\};\ s_{ik},\ u_{ik}\ge 0;\ i\in I; k\in K; l\in L;$

Minimization of the total value (1) ensures minimum costs related to rescheduling of electrical equipment assembly. The determined total cost includes the costs of assembly and the costs related to premature or delayed product assembly.

The constraints regarding models M1 and M2 ensure: (2) – distribution of all the assembly operations which cannot be performed as per the original schedule between the machines; (3) assembly as per original schedule for the products to which the rescheduling does not apply; (4) allocation of the appropriate types of operations to the assembly machines; (5) verification of restricted working space of the assembly machines, which means that the product component feeds allocated to the machines can fit into the working space of these machines; (6) elimination of allocating assembly operations to those machines which are technically incapable of performing them; (7) performing no more than one operation for the given product in the given period of time; (8) performing no more than one operation at a time by a machine, if this machine is available at this time; (9) – performing the given operation on one machine only; (10) – performing an operation on a machine only when this machine is ready for assembly; (11) – performing operations in accordance with technological restriction and continuity of operations; (12) – one-way flow of production along the assembly line; (13) – reserving the time needed for transporting the products between the machines.

The following group of constraints is related directly to the considered cost criterion. The constraints ensure: (14) – designation of the time of finishing the product assembly; (15) – designation the time of delay of the product assembly; (16) – designation of the time related to product delay in the case of which a unit penalty is charged and the decision about the penalty is encoded using variables w_k determined in constraint (17).

Constraints (18) and (19) ensure appropriate types of variables.

Constraint (20) applies only to M1 model. It ensures no-wait scheduling. Thanks to this constraint, the intervals between assembly operations concerning the given product are used only to transport the product between the machines.

The last group of constraints applies to the M2 model, in the case of which the machines can be blocked by products awaiting further operations. The constraints concerning only this model ensure: (21) – continuity of operations concerning the given product; (22) – determination of the start time for the given operation for a specific product; (23) determination of the stop time for time for the given operation for a specific product; (24) – determination of the duration of the machine being blocked by the given product; (25) – blocking of the given machine by the product before starting the following operation; (26) blocking of a given machine by the product directly after stopping the previous operation; (27) – lack of possibility for a machine to act as a buffer and performance of assembly operations at the same time; (28) and (29) – appropriate types of variables.

The number of periods H considered in the presented mathematical models can be estimated in accordance with the procedure published in study [4] or [14].

Computational experiments

The presented method was verified using computational experiments. The computations were made using solver GUROBI [15]. Thanks to these experiments, it was possible to compare the costs related to performance of electrical equipment assembly schedule using mathematical models M1 and M2. For this purpose, index α was defined in equation (29). The costs incurred as a result of using the schedule built with model M1 are marked as C^{M1}, while the costs related to application of the M2 model are marked as C^{M2}.

(29) $\alpha = \frac{C^{M1}-C^{M2}}{C^{M2}} \cdot 100\%$

The computational experiments concerned five groups of test tasks. For each group, 25 test examples were solved. The parameters of these task groups and the average values of the *α* index are shown in table 2.

Table 2. Parameters of 5 groups of test tasks and average values of indexes *α* [%]

Group	Parameters of test tasks					Index *α*
	M	*W*	W^1	*N*	*H*	
1	3	3	1	10	16	16.2
2	4	4	2	12	18	15.9
3	4	5	2	14	20	15.1
4	5	5	2	16	24	12.8
5	6	8	2	18	24	12.2

Numbers of: *M* - machines, *W* - types of products, W^1 – types of products mounted according to the original schedule, $k \in K^1$; *N* - types of assembly operations, *H* - periods.

The results of the computational experiments listed in table 2 show an increase in the assembly process cost in the case of using no-wait scheduling compared to letting the machines act as buffers. In the case of using the M1 model, the determined costs of the electrical appliance assembly process were 12–16% higher than the costs of assembly rescheduling in accordance with model M2.

The amount of the costs is largely affected by the fines for delays in the product assembly, as well as the costs of storing the products. Moreover, using no-wait scheduling resulted in determination of about 14–17% longer schedules than when the machines could have been blocked by products awaiting further operations. The schedule lengths C_{max} were determined based on the equation (30).

(30) $C_{\max} = \max_{i \in I, j \in J, k \in K, l \in L} \, lq_{ijkl}$

The schedule length is an important factor which affects the costs incurred. It should also be emphasized that the purpose of the method described was not to build the shortest possible schedules. The described method concerning rescheduling puts an emphasis on the deadlines of completing orders, as agreed with the recipients of the electrical equipment. Meeting the recipients' requirements is an important aspect of this method.

The computations were performed using CPU Intel Core i7-8550U 4GHz. The computation time was about 15 min. for tasks formulated for the first group 9 (Tab. 2), and about 40 min. for the fifth group of tasks.

Application of the monolithic method described herein had a positive impact on the quality of the solutions – the defined costs were optimal, about 3–5% lower than in the case of the hierarchical model – compared to the hierarchical method. The two-level method based on hierarchical model is detailed described in the paper [16]. The two sub-tasks were solved using this hierarchical method. The top-level was a stage loading, i.e., allocation of operations among the stages. The base-level was an operation scheduling – allocation of operations among the stations. The cost criterion was used in the minimization functions formulated for the base level. The methods were compared after modifying the mathematical model presented in this paper by removing constraints regarding rescheduling. The Application of the hierarchical method resulted in determination of schedules connected with bigger costs, but solutions were defined in a shorter computation time – by about 20%. The sub-tasks have about 40% less computational complexity in comparison to a global problem.

Conclusion

One very important advantage of the developed method is the possibility of making changes to existing schedules, adopting them to the variable conditions of the electric equipment assembly process. The determined schedules are characterized by the lowest costs of task completion. These schedules take into account new orders and limited availability of the machines. Rescheduling of assembly has a positive impact on the costs of the process, for instance the costs related to interruption of the assembly process in the case of restrictions in electricity supply. This problem is described in study [17]

Due to lack of intermediate buffers in the assembly line, two alternative possibilities of the product flow along the assembly system were proposed. This is the no-wait scheduling and the possibility of the machines being blocked by products awaiting further operations. Both variants of scheduling the electrical equipment assembly were compared using completed and described computational experiments. The advantages and disadvantages of both concepts were detailed.

One of the most important advantages of the developed method is the possibility of determining optimal schedules. This was achieved by using the monolithic approach to problem solving and application of integer programming, of course, using linear mathematical models with integer decision-making variables affects the amount of time required for the computations, particularly in the case of solving problems of relatively significant sizes. Yet, the current development if computer technology and software favours using the mathematical and IT tools employed in this method.

The presented mathematical models may be modified, adapted to the variable process of electric equipment assembly. In order to build new schedules in a relatively short time, they can be used in relaxation heuristics, such as e.g. in the case of the method described in study [14]. Relaxation of a model consists in removing the conditions of variable integrity from the model. Next, the variables are rounded off a preliminary schedule is verified and modified, in accordance with the principles described in the algorithm.

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