OPERATIONS SEQUENCING IN A CABLE ASSEMBLY SHOP

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Abstract: *The need for a better, compact and neat solution in the cable systems used by the automotive industry resulted in emerge of companies specialized in producing such cable systems. The present study is an extension of the work that was carried out for one such company. One of the main operations in the production of cable systems is the attachment of the connectors to the ends of the cables. This process is composed of cutting, stripping and crimping the cable ends. These operations are to be performed for each connecter attachment. Each connector type requires a different head for the crimping operation. Thus, the required setup time is doubled if the heads for both ends of the cable should be changed. The problem in hand is a TSP where the distances between the nodes are either one or two. An effective and simple heuristic algorithm is developed that yields either an optimum solution or one that is off by a few percent. Among nine experiments six resulted with optimum solution while the others deviated from the optimum at most one percent.*

Keywords: *TSP(1,2), Cable Assembly, Heuristics*

1. Introduction and Problem Definition

Production of cabling systems used by the automotive industry can get quite complicated due to different lengths, colors, diameters and connector types. One of the main operations in such production is the attachment of the connectors to the ends of the cables. This involves the operations of cutting, stripping and crimping of the cable ends which are to be performed for each connecter attachment. Since all of these operations are performed by the same machine we will regard them as a single operation. Different types of connectors require different types of heads. The setup time involved in changing the heads is the most time consuming operation, about 30 minutes for each. The worst case is obviously that where a group of cable requires both heads (one on each end) to be changed. This practically doubles the setup time where both heads cannot be changed simultaneously.

The aim of this study is to find the production sequence of a given set of cable batch, with different connectors, such that the requirement of changing both heads is minimized, thus reducing the total setup time. One should note that, the problem gets more complicated if the overall production of the batch needs to be assigned to several machines such that the concurrent usage of a particular head by more than one machine is to be avoided. Even though the problem can be overcome by keeping two or more heads of the same type it will increase the total cost. We note that, distribution of the production to two or more machines is a Vehicle Routing Problem, VRP, where the capacities of the machines are the weekly working hours. In the present study, we will not consider the case of more than one machine being involved in the production.

Duman et al. (2005) studied the same problem and formulated it as a TSP (1, 2) with distances of one or two. For more information on the TSP (1,2) formulation we refer the reader to the works of Fotakis and Spirakis (1998), Duman et al. (2005) and Papadimitriou and Yannakakis (1993). Duman et al. (2005) came up with a simple heuristic algorithm called the *Most Popular Connector First* (MPCF). Their approach requires starting the manufacturing sequence with the most popular connector; and proceeding to the next most popular one keeping the cable that provides only one head change as the last cable to be manufactured in the group. They have tested their algorithm using cable batches of 200 different cables with 50 different connector types. Their results showed 2.5-5% deviation from the lower bound which is equal to the number of nodes plus one (for the double setup to be made initially) if the number of disconnected node subsets is one. This corresponds to the case where all the nodes are connected. On the other hand, the lower bound is equal to the number of nodes plus the number of disconnected subsets. This can be understood easily if one represents the cable assembly problem graphically, Fig.1. Each letter in the graph represents a connector type and each circle represents a cable type. In this graphical representation, cable types having a common connector type are connected by an arc (indicating that distance will be one if these cables are produced consecutively), while cables having no common connectors are not connected.

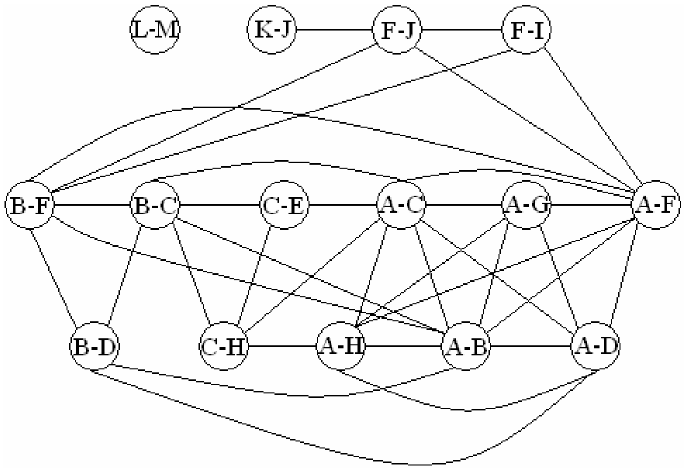

Fig.1 Graphical representation of a cable assembly problem

In this study, we propose a different heuristic approach named the *Least Popular Connector First* (LPCF). A detailed explanation of the algorithm will be given in the next section. Using the test data of Duman et al (2005) comparison of the LPCF and MPCF algorithms will be given in section 3. Finally the paper will end with a conclusion section.

2. Least Popular Connector First (LPCF) Algorithm

A cable is identified by the two connectors used at its ends. Thus, the algorithm requires that each connector type is uniquely defined. LPCF algorithm determines the production sequence of the cables mainly based on the popularity of the connectors used; that is, those with least popularities have the priority over the others. The popularity P_i of the i-th connector is defined as the number of its usage in the batch to be manufactured. Since there may be more than one connector with the same popularity, a given popularity will correspond to a subset of the cable batch to be produced. These cables will have the connectors with the given P_i at one end and connectors with popularities either equal to the given P_i or larger on the opposite end. Since the popularities of the connectors change as they get used in the production, LPCF algorithm is a dynamic one. Once the cables with connectors having the least popularity, P_{least}, are determined, the cable that will be produced is selected based on the connectors used on the opposite end; once again the connector with the lowest popularity is the determining factor. The production of the cables with the selected least popular connector type at one end will proceed in a manner such that, the last cable produced will have at the opposite end the connector with the largest popularity in that subset. This is the key factor in the LPCF algorithm. This particular connector will be labeled as the *bridge connector* and will be used to provide the passage to the next group of cables to be produced. Since the bridge connector has a large popularity, it also has a higher probability to provide the required passage to the next batch to be produced with a distance of one; namely, requiring only one head to be changed. The step by step description of the algorithm will now be given.

STEP 1: Calculate the number of usage/popularity, P_i, of each connector type to be used. Identify the one(s) with the least popularity, P_{least}. This group of connectors will be called the *preferred connector set*. If more than one connector type has the P_{least} popularity in the preferred connector set GO TO STEP 2, otherwise, produce the cable(s) leaving the cable with the highest popular opposite end connector to be produced last in the group. Identify this opposite end connector of the last cable produced as the *bridge connector*. Reduce the popularities of the connectors. GO TO STEP 1.

STEP 2: Each connector in the *preferred connector set* defines a group of cables having the preferred connector at one end and different connector at the opposite end. Each such group is called a *preferred cable* *set*. Each group is ordered within itself this time based on the popularities of the connectors used on the opposite end. If the bridge connector has already been defined, (undefined only at the very beginning of the algorithm) GO TO STEP 4.

STEP 3: Among the opposite end connectors of the *preferred cable set*, identify the one with the lowest popularity. Start the production of the cables belonging to this *preferred cable set*. The production should proceed such that the last cable produced has the most popular connector on its opposite end. Identify this most popular connector of the opposite end as the *bridge connector*. Reduce the popularities of the connectors used by the cables that have been produced and GO TO STEP 1.

STEP 4: Search to see if the *bridge connector* matches any one of the connectors in the *preferred connector set*. If there is no match GO TO STEP 5. Start the production of the *preferred cable set* whose *preferred connector* matches the *bridge connector*. The production should proceed such that the last cable produced has the connector with the highest popularity on its opposite end. Identify this most popular connector as the new *bridge connector*. Reduce the popularities of the connectors used. GO TO STEP 1.

STEP 5: Considering the *bridge connector,* identify all cables using the bridge connector at one of their ends. This set will be called the *bridge cable set*. Search to see if any of the connectors in this cable set matches the connectors on the opposite end of the *preferred cable sets*. If there are no matches go to STEP 6. If there is more than one match, then select the matching connector with the minimum popularity. Produce this cable and identify the opposite end connector as the new *bridge connector*. Reduce the popularities of the connectors used. GO TO STEP 1.

STEP 6: There is no connection between the previously produced set and the new *preferred cable sets*. This means both heads must be changed, corresponding to a distance of two in TSP (1, 2). Search the preferred cable sets for the opposite end connector having the lowest popularity. Starting with this particular cable, produce all the cables in the *preferred cable set* such that the last cable produced has the connector with the highest popularity on its opposite end. Identify this most popular connector as the new *bridge connector*. Reduce the popularities of the connectors used. GO TO STEP 1.

The above procedure continues until all the connectors have popularities equal to zero.

We will call each consecutive consideration of the STEPS 1 through 6, one iteration. If a tie occurs in any of the steps, choice between the equal elements will be made randomly.

The LPCF algorithm has several basic strengths. First, as it considers the connector types in an increasing order of their popularity, the chance of arriving at a passage with distance one is relatively high in the earlier iterations since connectors with high popularities have not been used up. Second, because the connectors with higher popularities are left to the end they again will have the greatest probability of providing a distance of one among themselves. Third, the bridge connector has a popularity of $P=P_{least}$ it also has high probability of providing a passage with distance of one.

Details of the first several iterations of the LPCF algorithm applied to set of cables given in Fig.1 will be now given. The resulting production sequence is given in Table 1.

The first iteration starts with the preferred connector set {E, G, I, K, L, and M}. The cables using these preferred connectors are (E^1-C^4), (G^1-A^6), (I^1-F^4), (K^1-J_2) and (L^1-M^1). The superscripts indicate the popularity of the particular connector at the beginning of the iteration. The cable (L^1-M^1) has the priority over the others because the opposite end connector M is also a preferred connector with popularity 1. Thus, the first cable to be scheduled for production is (L-M). The popularities are reduced and became L^0 and M^0. Since neither L nor M has a nonzero popularity bridge connector cannot be defined. This is also due to the fact that (L-M) is a disconnected set.

Next iteration starts with the preferred connector set {E^1, G^1, I^1, K^1}. The cables using these preferred connectors are, (E^1-C^4), (G^1-A^6), (I^1-F^4), and (K^1-J^2). The cable (K-J) has priority over others because the connector J has popularity of 2 which is lowest among the opposite end connectors, (A^6, C^4, F^4, J^2). The cable (K-J) is then scheduled as 2nd cable to be produced. The connector J is then assigned as the bridge connector. The new popularities of the connectors used are K^0 and J^1.

Next iteration starts with the new preferred connector set of {E^1, G^1, I^1, J^1}. Note that the usage of the connector J in the previous step placed it in the new preferred connector set with its new popularity of 1.

The cables using these connectors are (E^1-C^4), (G^1-A^6), (I^1-F^4), and (J^1-F^4). The bridge connector was J which allows a passage with a distance one to the cable (J^1-F^4). Thus, this is the next cable scheduled for production, (3rd cable). The new bridge connector is F and the new popularities of the used connectors are F^3 and J^0.

Next iteration, to determine the cable to be scheduled as the 4th in line, starts with the preferred connector set of the {E^1, G^1, I^1}. The associated cables are (E^1-C^4), (G^1-A^6) and (I^1-F^3). As seen the bridge connector F does not match any of the preferred connectors but supplies a passage with a distance one to the cable (I^1-F^3). Thus the 4th cable to be produced is (I^1-F^3). The new popularities are F^2 and I^0. The new bridge connector is again F.

The iteration to determine the 5th cable to be produced starts with the preferred set {E^1, G^1}; and the associated cables (E^1-C^4) and (G^1-A^6). The bridge connector F does not supply a direct passage to the preferred cables; thus one must consider the bridge cable set {(F^2-B^4), (F^2-A^6)}. The connector A^6 is common to both (F^2-A^6) bridge cable and (G^1-A^6) of the preferred cable set. Thus, (F-A) is scheduled. The new bridge connector is A. The popularities of the used connectors are F^1 and A^5.

The iteration for the 6th cable to be scheduled starts with the preferred set {E^1, G^1, F^1}; and the associated cables (E^1-C^4), (G^1-A^5) and (F^1-B^4). The bridge connector A supplies a direct passage to the preferred cable (G^1-A^5). Thus the cable to be scheduled for production is (G^1-A^5). The bridge connector is again A. The popularities of the used connectors are G^0 and A^4.

The preferred set of connectors for the next iteration is now {E^1, F^1}; and the corresponding cables are (E^1-C^4) and (F^1-B^4). Since the bridge connector A does not match with any of the connectors used by the preferred cables one must consider the bridge cables; {(A^4-C^4), (A^4-H^2), (A^4-B^4), (A^4-D^2)}. The bridge cable (A^4-C^4) allows a passage to the preferred cable (E^1-C^4) while (A^4-B^4) allows a passage to (F^1-B^4). To decide which to choose, one has to look at the popularities of the opposite end connectors; (B^4, C^4). There is an equality; because, both connectors have the popularity of 4. Hence, the choice must be made randomly; say C. Thus, (A^4-C^4) is scheduled to be produced as the 7th cable. The connector C is assigned as the new bridge connector and the popularities of the used connectors became A^3 and C^3. The remaining sequence is obtained in the similar manner.

Table 1 Production sequence of the cables given in Fig.1

Production No	End1	End2	Dist.	Production No	End1	End2	Setup
1	**L^1**	**M^1**	**2**	**9**	C^2	B^4	1
2	**K^1**	**J^2**	**2**	**10**	F^1	B^3	1
3	F^4	J^1	1	**11**	**C^1**	**H^2**	**2**
4	F^3	I^1	1	**12**	A^3	H^1	1
5	F^2	A^6	1	**13**	A^2	B^2	1
6	G^1	A^5	1	**14**	A^1	D^2	1
7	C^4	A^4	1	**15**	B^1	D^1	1
8	C^3	E^1	1	TOTAL SETUP			**18**

3. Experimentation results

As mentioned in the introduction, this study is an extension of a work carried out for a company producing cables for the automotive industry. The company produces around 200 products weekly composed of 50 different connector types. The popularity distribution of the connectors used shows a great similarity with the exponential distribution (some are used in large amounts while the majority is used in small amounts). Accordingly, in the test problems, 200 products were generated using 50 connector types with popularities showing exponential distribution. However, to see the performance of the algorithm in the case where the popularity distribution of the connectors was uniform, experiments with two sets of such data were run. These data sets were the same as Duman et al. (2005) used. The results of seven experiments carried on exponentially distributed connectors, indicated as E1, E2,…,E7 and two with uniform distribution, U1 and U2 are tabulated in Table 2.

Table 2 Comparison of LPCF and MPCF algorithms

Data	**Lower Bound**	**MPCF**	**LPCF**	**%Reduction in double setup**	**%Deviation from lower bound**
E1	201	208	201	100	0
E2	201	208	201	100	0
E3	201	206	203	50	1
E4	201	211	201	100	0
E5	201	210	201	100	0
E6	201	209	201	100	0
E7	201	209	201	100	0
U1	201	211	205	60	2
U2	201	218	204	82	1,5

The column called lower bound is, as defined earlier, equal to the number of nodes plus one (for the double setup to be made initially) if the number of disconnected node subsets is one. Since all the data used was a connected set, the lower bound is 200+1=201 for all cases. The columns MPCF and LPCF are the total setups predicted using the two algorithms Most Popular Connector First and the Least Popular Connector First respectively. Each double setup introduced in the production sequence increases the total setup by one. For example, the total double setups predicted by the LPCF algorithm was 1 (the only one required initially) while that predicted by MPCF was 8 (with seven additional double setups) in the case of data E1. Since the LPCF algorithm eliminated all the additional setup predicted by the MPCF algorithm, the percent reduction in the double setup was 100% which is indicated under the column named %Reduction in Double Setup. The last column shows the percentage deviation of the solution obtained by the LPCF algorithm from the lower bound.

As seen 6 out of 7 experimentations performed on the cable batch with exponential distribution resulted in the optimum solution recovering all the double setups. In the case of uniformly distributed connector sets the improvement was 60% and 82%. The last column shows the deviations of the LPCF results from the lower bounds. Once again the results are extremely good.

4. Summary and Conclusions

In this study, an industrial application of TSP with distances one and two in cable cutting and assembly shops is introduced and discussed. A simple heuristic solution is proposed to find the production sequence of the cables to be manufactured such that the total setup time is minimized. The heuristic approach utilizes the number of popularity of each connector to be used in the production, giving priority to those connectors with smaller popularities. Due to this character, the method is called the Least Popular Connector First, LPCF. The proposed algorithm was tested against a similar heuristic algorithm proposed in an earlier work of Duman et al. (2005) called the Most Popular Connector First, MPCF. The LPCF algorithm, proposed in this study, reduced the total setup time further by reducing the number of double setups corresponding to changing both heads used on the connector crimping machines.

As a future work, implementation of the LPCF algorithm to the case where more than one machine is involved in the production is to be studied. We note that, distribution of the production to two or more machines is a Vehicle Routing Problem, VRP, where the capacities of the machines are the weekly working hours. It will also be nice to extend the approach presented here to other possible application areas of TSP(1,2).

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