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Integrating Tier-1 module suppliers in car sequencing problem

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Abstract: The objective of this study is to develop a car assembly sequence that is mutually agreed between car manufacturers and Tier-1 module suppliers such that overall modular supply chain efficiency is improved. In the literature so far, only constraints of car manufacturers have been considered in the car sequencing problem. However, an assembly sequence from car manufacturer imposes a module assembly sequence on Tier-1 module suppliers since their assembly activities are synchronous and in sequence with assembly line of that car manufacturer. An imposed assembly sequence defines a certain demand rate for Tier-1 module suppliers and has significant impacts on operational cost of these suppliers which ultimately affects the overall modular supply chain efficiency. In this paper, a heuristic approach has been introduced to generate a supplier cognizant car sequence which does not only provide better operational conditions for Tier-1 module suppliers, but also satisfies constraints of the car manufacturer.

Key words: car sequencing, module assembly, synchronous assembly.

1. Introduction

Car manufacturers have been seeking ways for more flexible and efficient processes to cope with the evolving environment of the automotive industry. In this regard, modules are perceived as an engineering tool for companies to manage complex products by dividing them into sub-assemblies. Modular assembly concept offers car manufacturers the ability of efficient mass customization by enabling the postponement of final assembly of a product until customer orders have been received (Fredriksson and Gadde, 2005). One of the distinctive characteristics of modularity is synchronous production. Synchronous production is defined by Doran (2002) as an integrated supply chain approach which ensures delivery of products that are defect-free and match the exact requirements of the customer reflecting vehicle rather than model. Because of this production model, there is high pressure on the module suppliers since the whole vehicle assembly process at car manufacturer depends on the timely delivery of their modules in the right sequence (Larsson, 2002). Assembly sequence of the car manufacturer imposes a module assembly sequence on Tier-1 module suppliers since their assembly activities are synchronous and in sequence with assembly line of that car manufacturer. An imposed assembly sequence defines a certain demand rate for Tier-1 module suppliers and has significant impacts on operational cost of these suppliers which ultimately affects the overall modular supply chain efficiency.

In this study, we try to develop a car assembly sequence that is mutually agreed between car manufacturers and Tier-1 module suppliers such that overall modular supply chain efficiency is improved.

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2. Literature review

Car sequencing in mixed model assembly line depends on the controlling goals or purposes, such as to minimize the variation in rate of consuming the parts of the sequence (Monden, 1998). Gottlieb et al. (2003) explained that common car sequencing problems in the literature involve scheduling cars along an assembly line where options are installed at different assembly stations. These assembly stations are designed to handle a certain percentage of the entire assembly work while cars are passing along the assembly line. This approach intends to minimize work overload at any assembly station. Installing different options at a station results in various assembly times faced by that station. If car sequence lets several consecutive cars with same options which require longer assembly time to be assembled at a certain assembly station, then work overload is possible at that station. When workers get too much workload, there is a high possibility of making assembly mistakes which leads to increase in cost of quality or causing a line stoppage in the worst case. On the other hand, the workers in the successive stations may be idle while waiting for those options to be installed at that earlier assembly station and this leads again to higher production cost. Therefore, cars requiring this option must be spaced such that the capacity of the station is never exceeded. Parrello et al. (1986) and Solnon et al. (2008) introduced sequencing rules H_o:N_o for each labour-intensive option *o*, which restrict the occurrence of this option to at most H_o in any subsequence of N_o successive models. The goal is to find a sequence, which does not violate any of the given sequencing rules or – if such a sequence is not existent – minimizes rule violations. Boysen et al. (2009) define this sequencing rule as of type H_o:N_o, which means that out of N_o successive models, only H_o may contain the option *o* in order to avoid work overload. This is also known as the option rule in the literature. Drexl and Kimms (2001) provide an intuitive example:

> “Assume that 60% of the cars manufactured on the line require the option ‘sunroof’. Moreover, assume that five cars pass the station where the sunroofs are installed during the time for the installation of a single copy. Then, three operators (installation teams) are necessary for the installation of sunroofs. Hence, the capacity constraint of the final assembly line for the option ‘sunroof’ is three out of five in a sequence, or ‘3:5’ for short.”

Since 70% of the car value is built on the assembly line on the average, car sequencing problems in the literature considered final assembly line constraints that ensure load balancing and component supply to find an assembly sequence (Gagne et al., 2006).

In the literature, workload balancing or minimizing work overload and levelling component usage are two basic objectives of sequencing. The CSP is strongly NP-hard (Estellon and Gardi, 2006). To solve a CSP problem with one hundred or so vehicles and few options, the use of constraint programming or integer programming has limits and several heuristics have been proposed such as ant colony optimization, greedy algorithms or local search (Estellon et al., 2008).

Many researchers studied car sequencing problem with component levelling objectives, mainly as a key element of JIT philosophy, but none has considered constraints of module assembly in that problem as a synchronous production and in-sequence delivery concept. Module suppliers are critical partners in the automotive supply chain due to characteristics of synchronous production and delivery. Due to the same characteristics, module suppliers are directly affected by production scheduling process of car manufacturer, especially car sequencing. Assembling modules that are synchronized with car assembly line and delivering them in sequence leave no room for module suppliers to implement their own production schedules but to follow the one from car manufacturer. Therefore, car sequence of the car manufacturer is directly affecting production output and productivity of module suppliers. Car sequence generated by any available algorithm imposes an assembly sequence on Tier-1 module suppliers, which ultimately defines the requested demand rate from these suppliers.

In this study, a car assembly sequence that is mutually agreed between car manufacturer and module suppliers is developed. The proposed approach considers not only the objectives of car manufacturer, as all academic studies have done so far, but also the operational constraints of Tier-1 module suppliers since assembly activities of these suppliers are synchronous with assembly line of car manufacturers.

3. Impact of car sequencing on Tier-1 module suppliers

Figure 1 illustrates a common module call-off and sequential delivery process of Tier-1 module suppliers to car manufacturers following the vehicle assembly sequence. A, B and C represent car models to be produced where their subscripts define options of these vehicles. Respective modules are assembled and delivered to the car assembly line by Tier- 1 module suppliers matching with the car assembly sequence at the car manufacturer accordingly.

In Figure 1, there are five cars to be assembled in a sequence which is planned earlier by the car manufacturer (i.e. A_1, C_1, A_2, B_1, A_1). Notations of car models A, B and C present their options meaning that car model A has two available options (i.e. A_1 and A_2), whereas car model B and car model C have only single option (i.e. B_1 and C_1). These cars consist of three modules (i.e. *Module x*, *Module y*, and *Module z*), which are to be assembled at their respective assembly stations (i.e. *Station x*, *Station y*, and *Station z*). These modules are provided by different suppliers. *Module x* is supplied solely by Supplier 1 for all car models. *Module y* is supplied by two different suppliers (i.e. Supplier 2 and Supplier 3). Supplier 2 assembles and delivers *Module y* for car model A, whereas Supplier 3 assembles and delivers *Module y* for car models B and C. In case of *Module z*, there are three module suppliers, and each supplier supplies only one car model (i.e. Supplier 4 for car model A, Supplier 5 for car model B, and Supplier 6 for car model C).

In case of Supplier 1, the module supplier is responsible for building all necessary modules for all car models produced by the car manufacturer and adjusting the sequence of the modules according to the car assembly sequence defined by the car manufacturer. This case is relatively simple to manage for both the car manufacturer and the module supplier. It is even feasible to match module assembly sequence in the module supplier exactly with the car assembly sequence at the car manufacturer. It is also possible that modules for each car model are supplied by different module suppliers, such as Module z case. In this case, each module supplier receives assembly work order for the respective car model as well as the overall car assembly sequence for reference since each supplier is responsible for sequential delivery. After assembly of respective module by each supplier, these modules should be placed in the correct sequence that matches with

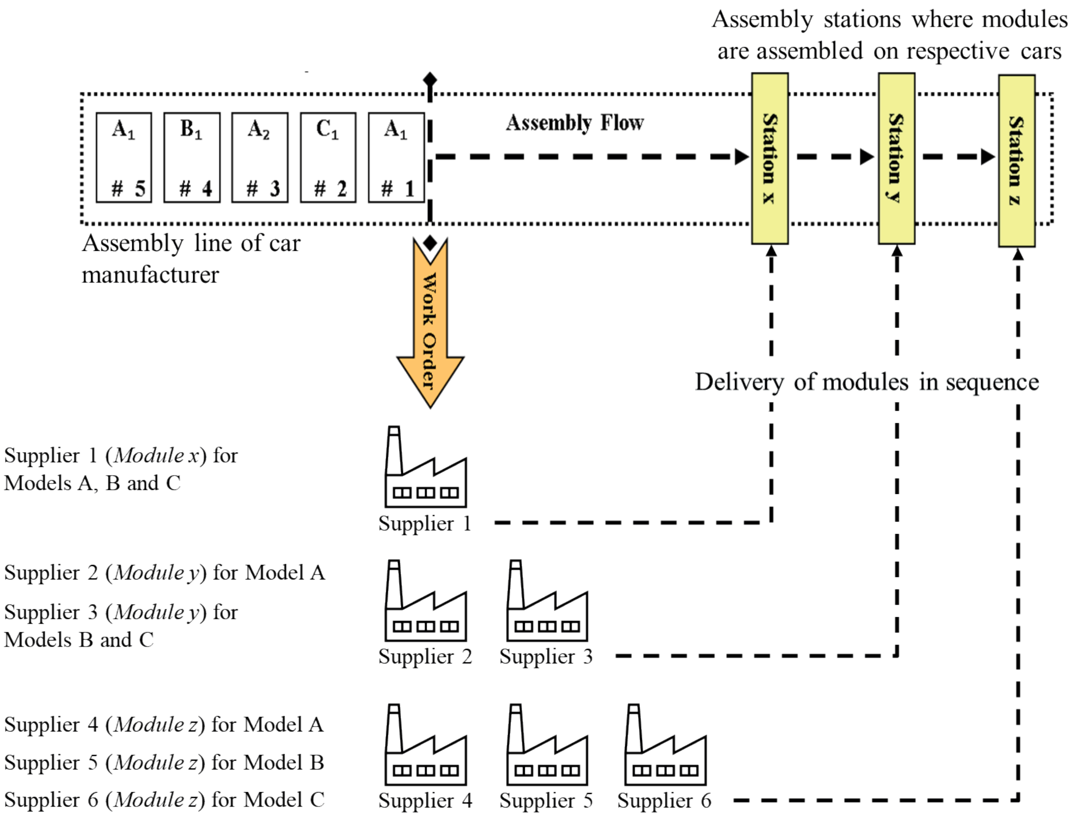

Figure 1. Tier-1 module call-off and sequential delivery concept in automotive industry.

the car assembly sequence of the car manufacturer. At this stage, owing to complexity of the delivery process, information exchange between all parties becomes extremely critical, and the involvement of the car manufacturer is unavoidable to define, and lead tasks related to delivery process and responsibilities between module suppliers.

Assembly work at a Tier-1 module supplier starts only when an assembly order from car manufacturer is received. After assembly process is completed, delivery of assembled modules is done respecting the car assembly sequence and within the given time frame defined by the car manufacturer. Due to the nature of synchronous production, module suppliers have different operational challenges than just-in-time (JIT) suppliers. A JIT component only becomes critical when stock levels of supplier are insufficient to meet forecast order volumes (Hellingrath, 2008). In contrast, a Tier-1 module supplier must be ready for production at any time as required by nature of synchronous production concept. It is obliged to assemble and deliver modules as soon as an assembly order from the car manufacturer is received. Therefore, its module is a critical component, and the capacity of Tier-1 module supplier becomes critical as well. Assembly line of module supplier is designed bearing in mind average production output of the car manufacturer. Workforce assigned for module assembly job is also defined and dispatched to module assembly line according to this average output level. If a car manufacturer follows a uniform demand rate d that is equal to this average output, workload at the module supplier would be quite balanced following car manufacturer's assembly line speed. However, a fluctuating demand rate from the car manufacturer would result in a changing workload at the assembly line of the module supplier. At a lower than average demand rate, assembly line workers at the module supplier would be facing idle time. On the contrary, when the demand rate is higher than average demand rate, the module assembly line workers would be overloaded at their respective assembly stations. In order to cope with such workload conditions at module suppliers, car manufacturer and module suppliers usually agree on a certain flexibility in addition to an average demand rate d. This flexibility is necessary for avoiding any possible vehicle assembly line stoppages at the car manufacturer. It is termed as "flexibility corridor" in the literature. The flexibility corridor is defined by a negotiable percentage of the contract volume, where the supplier is obliged to cover all requests (Niemann et al., 2019). If actual volume goes beyond this flexibility corridor (i.e. maximum volume level), then additional measures must be taken such as additional line investment and/or hiring additional workforce. Therefore, an improvement in the overall modular supply chain seems to be feasible by reducing this gap as much as possible. However, module supplier alone is not able to reduce this gap without cooperation of the car manufacturer.

Module supplier that faces a big demand drop would have to deal with operational issues such as unstable inventory, excess assembly line capacity, idle workforce, and fixed operational costs. On the other hand, if total output of the car manufacturer is stable, other module supplier providing modules to other car models at the same assembly line of the car manufacturer would face an opposite trend, an increase in demand. At the end, car manufacturer may offer the former supplier a huge compensation amount for its loss due to missing volume of the project, meanwhile it had to settle capacity issues with the latter supplier. Otherwise car manufacturer might review its strategy to outsource modules to avoid such schedule related economic impact on module suppliers. This economic impact seems to be avoided only if modules for all car models are provided by one module supplier. Since, regardless of the vehicle mix and individual models, module supplier is obliged to respond to the whole vehicle schedule and sequence, it would be exposed to total production volume of the car manufacturer as demanded volume instead of only one specific car model. However, allowing only one module supplier for all the cars on the assembly line leads to a monopoly at the end. In that case, purchasing power of car manufacturer over the module suppliers will be damaged, which might lead to other commercial issues between car manufacturer and the module suppliers.

A heuristic approach has been introduced to show the impact of car sequencing on Tier-1 module suppliers and to generate a supplier cognizant car sequence trying to eliminate this impact. We start by generating a car sequence as a first step and review impacts of this car sequence in terms of demand imposed on Tier-1 module suppliers by the car manufacturer. Afterwards, possibility of improvement is studied by involving Tier-1 module suppliers in the car sequencing problem. Figure 2 shows the methodology used in this study.

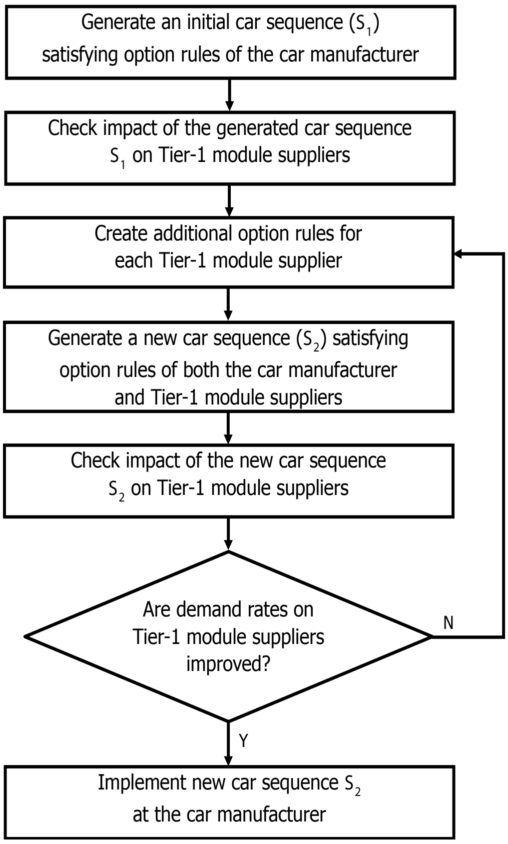

Figure 2. Methodology to develop supplier cognizant car sequencing.

4. Car sequencing problem

Car sequencing problem is a well-studied problem in literature as well as in the automotive industry. In this study, we have used the car sequencing algorithm written in Java programming language by LocalSolver (Benoist et al., 2011), a French software editor company, specializing in the field of optimization and decision support. LocalSolver utilizes a hybrid approach of very large-scale neighbourhood search (VLNS) and very fast local search (VFLS), which is the best-known approach for solving car sequencing problems (Regin and Puget, 1997; Estellon et al., 2006; Estellon et al., 2008). It is claimed to have a hybrid local search heuristic based on very fast explorations of small neighbourhoods (Benoist et al., 2011). The algorithm applies one transformation at each iteration to the current sequence which modifies it only very locally. Pseudo code of the algorithm is shown in Figure 3.

Once initial sequence is built by a greedy algorithm, five basic transformation strategies are used in the algorithm as listed below: swap, forward insertion, backward insertion, reflection, and random shuffle (Estellon et al., 2008).

In this section, sample problem carseq_300_8_20_25 from CSPLib (Gagne et al., 2006) is used in order to analyze the feasibility and efficiency of the proposed supplier cognizant car sequencing concept. All numerical experiments were performed on a standard computer equipped with the operating system Windows 10 64-bits and the chip Intel Pentium G3420 (3.20 GHz, RAM 4 GB). The problem is defined as shown in Figure 4.

300 cars must be manufactured in this problem. The number of options is 8, and the class size is 20. First line of the problem states the number of cars (i.e. total demand) that are to be produced; number of options available for these cars and number of classes (i.e. number of car models) in this demand

```
Algorithm LocalSolver
Begin;
  compute initial sequence;
  while number of violations > 0 and execution time limit is not reached do
    choose transformation (swap, forward/backward insertion, reflection or shuffle) and positions where applying it;
    if transformation does not result in a higher number of violations compared to current sequence then
      update current sequence by performing it;
    end if;
  end do;
  return current sequence;
End;
```

Figure 3. Pseudo code of the car sequencing algorithm.

```
300 8 20

2 1 2 1 3 1 1 2
3 3 4 3 5 3 3 4

0  13 1 0 0 0 0 0 0 0
1  19 0 1 0 0 0 0 0 0
2  12 0 0 1 0 0 0 0 0
3  19 0 0 0 1 0 0 0 0
4  11 0 0 0 0 1 0 0 0
5  26 0 0 0 0 0 1 0 0
6  16 0 0 0 0 0 0 1 0
7  18 0 0 0 0 0 0 0 1
8  18 0 1 0 1 1 1 0 0
9  10 0 0 1 1 0 1 0 0
10 14 1 0 1 0 0 0 0 0
11 10 0 0 1 0 0 0 1 0
12 14 1 0 0 0 1 1 1 1
13 14 0 1 1 0 0 0 0 0
14 13 0 0 1 0 1 1 1 0
15 14 0 0 0 0 1 1 0 0
16 15 0 1 0 1 0 0 1 1
17 18 1 1 0 1 0 0 1 0
18 11 1 0 0 0 0 0 1 0
19 15 1 1 1 1 1 0 0 0
```

Figure 4. CSPLib Problem carseq_300_8_20_25.

package. Second and third line of the problem define the option rules. For each option (columns), the maximum number of cars allowed with that option in a block (second line) and the block size (third line) are shown. The rest of the problem presents car model in the first column (i.e., model index number); number of cars to be produced for this model in the second column; and for each option (remaining columns), whether this model requires this option or not (1 or 0).

A feasible solution (i.e. assembly sequence for 300 cars) with zero violation obtained by LocalSolver after 2,207,246 iterations in 44 seconds is shown in Figure 5. The number at the first row shows the number of option rule violations achieved by the proposed car sequence. Index of car classes is shown in the car sequence from the second row onwards. The table must be read from the left to the right and from the top to the bottom. Therefore, feasible car sequence starts with the first car at the first column in the second row and is followed by its successor car on its right in the table.

Let us assume that a module supply chain is involved in this production and two module suppliers are delivering *Module X* (such as seat module) to the car manufacturer but for different car models. Naturally, variants of *Module X* for different car models are different from each other. However, product structure and characteristics in each *Module X* are similar, therefore it is feasible that *Module X* for each model can be assembled on the same assembly line at both module suppliers. Let us define two Tier-1 module suppliers delivering *Module X* for the car models presented in the CSPLib Problem carseq_300_8_20_25 as *Supplier A* and *Supplier B*. Let us also assume that *Supplier A* assembles and delivers modules for car models (or car classes) from number 0 to number 8, and *Supplier B* assembles and delivers modules for car models from number 9 to number 19. Since a feasible car sequence is generated, following this car sequence, a demand would be imposed on these Tier-1 module suppliers. *Supplier A* and *Supplier B* synchronize their module assembly lines with the assembly line of the car manufacturer following this car sequence. Let us consider that production rate at the car manufacturer (p) is 15 cars per hour. It means that completing assembly of 300 cars is a matter of 20 hours. *Supplier A* is assigned to assemble and deliver modules for 152 cars out of 300 cars to be produced. Remaining demand of 148 cars is to be supplied by *Supplier B*. In an ideal case, following their demand of 152/300 cars and 148/300 cars, *Supplier A* and *Supplier B* would follow an hourly demand rate of 7.6 modules per hour and 7.4 modules per hour respectively. Therefore, we can consider that average hourly demand rate of 7

```
0

8  11 4  8  10 11 8  4  7  16 15 4  17 5  4  17 5  7  17 5  0  16 5  0  17 5  10 16 5  0
16 5  0  16 5  7  19 14 7  3  14 13 3  12 7  19 4  18 8  10 6  8  10 18 8  0  6  19 5  6
19 5  6  19 5  6  1  9  11 1  3  12 13 3  14 1  3  12 1  7  14 1  3  12 13 3  14 7  19 12
2  7  17 15 7  16 5  4  16 15 2  17 5  0  17 5  2  17 5  10 16 15 0  16 15 0  17 5  0  17
15 10 17 5  2  16 5  7  17 5  10 17 5  4  13 12 3  1  14 3  13 6  9  1  18 9  1  18 9  1
6  9  1  6  9  1  18 9  1  11 5  19 6  5  19 11 4  8  18 10 8  6  10 8  18 10 8  11 7  8
6  10 8  11 7  8  6  2  19 12 7  19 5  6  19 15 2  16 5  0  17 15 2  16 15 2  17 15 7  17
15 10 16 15 0  16 5  10 16 15 2  17 15 7  17 5  7  19 12 2  1  14 3  13 12 4  13 14 3  1
14 3  1  14 3  13 12 4  19 6  2  8  18 0  8  11 7  8  11 10 8  6  0  8  11 7  19 12 2  1
14 3  13 18 9  1  18 9  13 18 3  13 12 3  1  14 3  13 12 3  13 14 3  1  6  9  13 4  12 19
```

Figure 5. Feasible solution for CSPLib Problem carseq_300_8_20_25.

or 8 modules are two acceptable workload scenarios for these module suppliers. However, car sequence generated in Figure 5 imposes actual demand rates on both suppliers which are quite different than the ideal case. Table 1 shows this actual demand that both suppliers face for 20 hours (based on 15 cars per hour production rate of the car manufacturer). It can be observed that during 20 hours of production, there are 10 production windows (i.e. one-hour production time) when *Supplier A* and *Supplier B* are facing either higher or lower hourly demand rates than their average hourly demand rate. Specifically, at 15^{th} and 19^{th} hours, it can be observed that the gap between actual demand rates and average demand rates for both suppliers are big. *Supplier A* is facing idle time due to lower demand rate than its average demand rate (47% lower at 15^{th} hour and 34% lower at 19^{th} hour). On the contrary, *Supplier B* is overloaded with higher demand rate than its average demand rate (49% higher at 15^{th} hour and 35% higher at 19^{th} hour). The remaining 8 production windows, when average demand rate is not followed, also impose a demand fluctuation of approximately 20% on both suppliers.

Table 1. Hourly demand rate of module suppliers. (*Unit: number of modules*).

	Supplier A	*Supplier B*
1^{st} hour	9	6
2^{nd} hour	9	6
3^{rd} hour	8	7
4^{th} hour	9	6
5^{th} hour	8	7
6^{th} hour	8	7
7^{th} hour	8	7
8^{th} hour	7	8
9^{th} hour	7	8
10^{th} hour	7	8
11^{th} hour	8	7
12^{th} hour	8	7
13^{th} hour	9	6
14^{th} hour	6	9
15^{th} hour	4	11
16^{th} hour	8	7
17^{th} hour	9	6
18^{th} hour	9	6
19^{th} hour	5	10
20^{th} hour	6	9

5. Supplier cognizant car sequencing

The purpose of supplier cognizant car scheduling is to avoid any idle time or work overload at the module suppliers if possible. It means that the hourly demand rate faced with each module supplier needs to be distributed as uniform as possible over the production time. In this section, possibility of improving the gap between actual demand rate and average demand rate for *Supplier A* and *Supplier B* have been studied by involving them in the car sequencing problem.

We integrate Tier-1 module suppliers in the car sequencing problem by utilizing option rules. We introduce modules of *Supplier A* and *Supplier B* as additional options for each car model (i.e. number of options in CSPLib carseq_300_8_20_25 increases from 5 to 7). Only one module (either delivered by Supplier A or Supplier B) can be assigned to a car model. Afterwards, we must define option rules for these modules. The aim of the supplier cognizant car sequencing is to provide Tier-1 module suppliers a uniform demand rate as smooth as possible. Therefore, we need to consider the size of production rate of the car manufacturer as block size for module options.

At this point, we would like to calculate average demand rate for *Supplier A* and *Supplier B*. It is worth mentioning that demand rate is important for these suppliers as they can calculate their necessary takt time and design their module assembly lines accordingly. For any Tier-1 module supplier s ($s=1,..,S$), whose assembly line is synchronized with the assembly line of the car manufacturer, average demand rate of the supplier (d_s) can be calculated as;

$$d_s = p \cdot \frac{\textit{Module demand to be supplied by suppliers}}{\textit{Total number of cars to be produced}} \quad (1)$$

where. $\sum_{s=1}^{S} d_s = p$

Following Equation (1), we can calculate average demand rates for *Supplier A* and *Supplier B* as below.

$$d_A = 15 \cdot \frac{152}{300} = 7.6 \ \textit{modules per hour}$$

$$d_B = 15 \cdot \frac{148}{300} = 7.4 \ \textit{modules per hour}$$

Now, we can define the option rules for these modules from *Supplier A* and *Supplier B*. Option block sizes will be equal to car manufacturer's production rate p (15 modules per hour or 15 cars in one hour) since it was the base for calculating average demand rates of module suppliers as well. Within this block size of 15 cars, we expect to see 7.6 cars equipped with modules from *Supplier A* and 7.4 cars equipped with modules from *Supplier B*. Therefore, we need to allow 8 cars in a row of 15 cars for modules from *Supplier A* and 8 cars in a row of 15 cars for modules from *Supplier B*. The methodology of integrating module suppliers in car sequencing problem can be summarized as below:

Step 1. Consider each module supplier as an artificial car option. Add one new car option for each module supplier.

Step 2. For the newly added car option, set block size equal to the production rate of the car manufacturer (i.e. cars per hour).

Step 3. Calculate average demand rate for each module supplier using Equation (1) and set maximum number of allowed cars in newly added car option block equal to the closest higher integer value ($\lceil d_s \rceil$).

Step 4. Assign module suppliers to respective car models.

Modified CSPLib Problem carseq_300_8_20_25 is shown in Figure 6. A feasible car sequence is obtained by LocalSolver without any violations after 49,944,691 iterations in 1,386 seconds as shown in Figure 7.

```
300 10 20

2 1 2 1 3 1 1 2 8  8
3 3 4 3 5 3 3 4 15 15

0 13  1 0 0 0 0 0 0 0 1 0
1 19  0 1 0 0 0 0 0 0 1 0
2 12  0 0 1 0 0 0 0 0 1 0
3 19  0 0 0 1 0 0 0 0 1 0
4 11  0 0 0 0 1 0 0 0 1 0
5 26  0 0 0 0 0 1 0 0 1 0
6 16  0 0 0 0 0 0 1 0 1 0
7 18  0 0 0 0 0 0 0 1 1 0
8 18  0 1 0 1 1 1 0 0 1 0
9 10  0 0 1 1 0 1 0 0 0 1
10 14 1 0 1 0 0 0 0 0 0 1
11 10 0 0 1 0 0 0 1 0 0 1
12 14 1 0 0 0 1 1 1 1 0 1
13 14 0 1 1 0 0 0 0 0 0 1
14 13 0 0 1 0 1 1 1 0 0 1
15 14 0 0 0 0 1 1 0 0 0 1
16 15 0 1 0 1 0 0 1 1 0 1
17 18 1 1 0 1 0 0 1 0 0 1
18 11 1 0 0 0 0 0 1 0 0 1
19 15 1 1 1 1 1 0 0 0 0 1
```

Figure 6. Modified Problem carseq_300_8_20_25.

This new car sequence does not only provide better operational conditions for Tier-1 module suppliers, but it also satisfies constraints of the car manufacturer. Therefore, in addition to the benefits of supplier cognizant car sequencing to Tier-1 module suppliers and therefore to module supply chain, it does not have any negative impact on the car manufacturer in terms of car sequencing. Figures 8 and 9 present the hourly demand rates for *Supplier A* and *Supplier B* respectively during 20 hours of production for both initial car sequence case and modified car sequence (i.e. supplier cognizant car sequence) case.

Table 2. Hourly demand rate of module suppliers (supplier cognizant car sequence). (*Unit: number of modules*).

	Supplier A	*Supplier B*
1st hour	8	7
2nd hour	8	7
3rd hour	8	7
4th hour	7	8
5th hour	8	7
6th hour	7	8
7th hour	8	7
8th hour	8	7
9th hour	7	8
10th hour	7	8
11th hour	8	7
12th hour	7	8
13th hour	8	7
14th hour	7	8
15th hour	8	7
16th hour	7	8
17th hour	8	7
18th hour	7	8
19th hour	8	7
20th hour	8	7

```
0

8  18 2  8  11 7  19 5  6  19 15 6  13 9  6  1  9  18 1  9  6  1  9  6 1  9  18 1  9  6
13 3  12 13 4  11 8  10 6  8  7  11 8  10 6  19 7  12 13 3  14 7  19 5 4  17 5  4  16 15
4  17 15 7  16 5  0  16 5  0  17 5  10 17 5  0  17 15 7  17 5  4  16 5 10 17 4  15 16 2
5  16 7  15 17 7  5  16 0  5  16 10 5  17 7  5  16 2  15 17 0  5  19 4 12 13 3  14 1  3
12 13 3  14 1  3  14 13 3  12 13 3  14 1  3  12 13 3  14 1  3  12 13 3 14 1  2  12 19 7
14 1  3  12 2  19 12 7  19 5  6  13 9  6  1  9  11 4  8  18 10 8  18 4 8  11 10 8  6  10
8  11 7  8  11 10 8  18 0  8  18 10 8  18 7  19 14 0  1  14 3  13 12 3 1  12 3  13 12 3
13 14 3  1  14 3  1  14 0  19 5  0  17 15 0  16 15 2  17 5  4  16 5  7 17 0  5  16 10 15
17 4  7  16 5  2  16 5  10 16 7  5  17 2  15 17 0  15 17 2  5  17 7  15 6 19 5  11 1  9
18 1  9  18 0  8  11 2  1  12 2  19 6  5  19 18 15 19 11 7  8  6  10 8  6 10 8  6  2  19
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Figure 7. Feasible solution for modified Problem carseq_300_8_20_25.

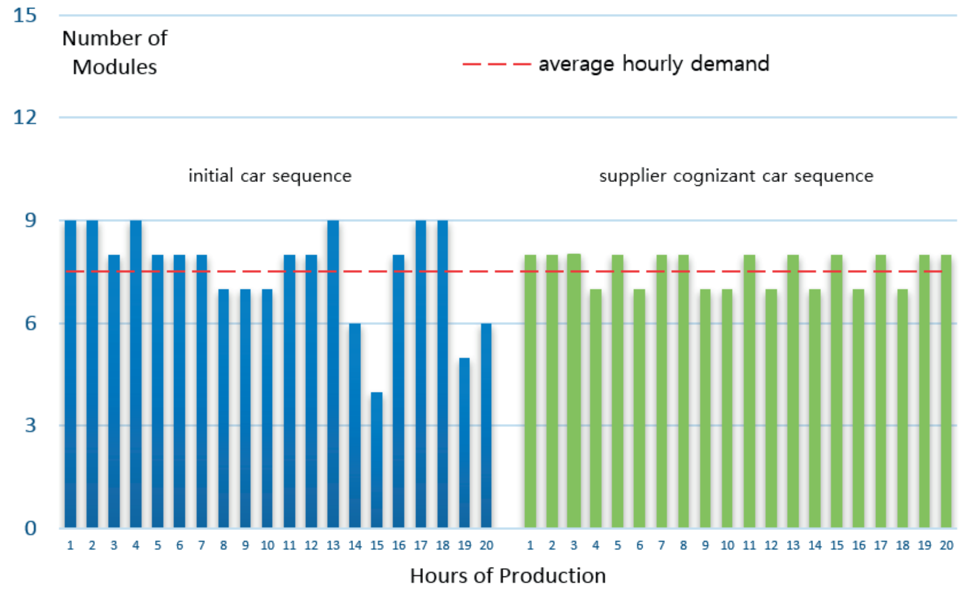

Figure 8. Change in hourly demand rate of *Supplier A*.

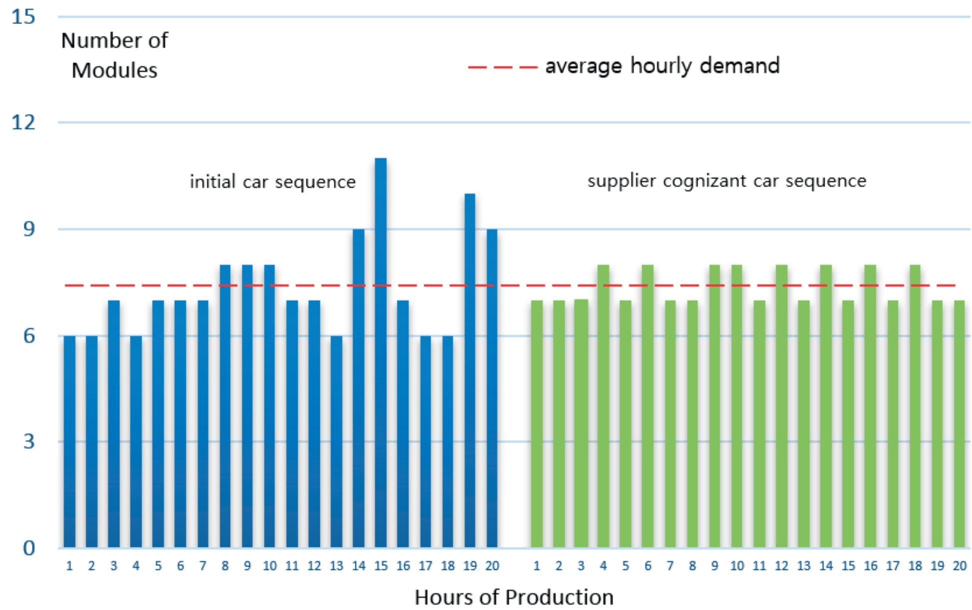

Figure 9. Change in hourly demand rate of *Supplier B*.

6. Conclusion

In this research, we endeavoured to show the impact of car assembly sequence, which is imposed by car manufacturer on Tier-1 module suppliers. As this impact affects the cost performance of the module supply chain, we argued that car sequencing, which is done by the car manufacturer, should consider modules as one of constraints while deciding car sequence to be assembled to lessen this impact. As there is no such study in the literature so far, we suggested a new approach to integrate module assembly in the car sequencing problem. We proposed a supplier cognizant car assembly sequencing concept by adding module suppliers as options and defining their option rules following the average demand rates they are required to respond to. The main reason behind suggesting a supplier cognizant car assembly sequence is to avoid idle time or work overload of assembly operators at module suppliers that is caused by an imposed car assembly sequence. Both idle time and work overload happening at module suppliers lead to wastage of resources and have cost impact on the module suppliers as well as overall module supply chain. The overall module supply chain profitability would improve if the module supply chain cost could be reduced by implementing a supplier cognizant car sequencing, which targets to satisfy both operational constraints of car manufacturer as well as module suppliers. At the end, we showed that a car assembly sequence, which still satisfies the workload requirements of the car manufacturer and respects workload of module assembly line of Tier-1 module suppliers, is possible.

Option rules were used as hard constraints for car sequencing problem. The option rules were defined considering requirements of car manufacturer and operational constraints of module suppliers. Further studies can be conducted by using soft constraints. This approach would allow having different weights for operational constraints of car manufacturer and Tier-1 module suppliers. At the end, some constraints imposed by car manufacturer may have priority over operational constraints of Tier-1 module suppliers, therefore they should be respected even if they might end up resulting in certain cost due to unsatisfied operational constraints of those module suppliers. Moreover, this study can be enhanced by exploring different volume scenarios between module suppliers, which may reduce the impact imposed by car manufacturer on the module suppliers.

The implications of this study for manager of car manufacturers are clear. The improvement possibility of the Tier-1 module supply chain is evident and worth exploring. Supplier cognizant car sequencing does not only eliminate waste of resources but also ensures reliability of module supply chain by eliminating high demand fluctuations. Depending on several factors such as which modules to consider and to what extent supplier cognizant car sequencing can be realized, performance of the concept will differ.

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