Research Article.
Journal of Intelligent Systems: Theory and Applications 4(1) (2021) 24-36
DOI: 10.38016/jista.767154

A Tabu Search and Hybrid Evolutionary Strategies Algorithms for the Integrated Process Planning and Scheduling with Due-date Agreement

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Abstract
There are three important functions of manufacturing which are process planning, scheduling and due date assignment. Instead of executing these functions separately, combining them together helps making more realistic and applicable plans. In this problem context random search, semi-tabu, random/semi-tabu hybrid, evolutionary strategies, and random/evolutionary strategies hybrid methods are utilized in solution. Different sized job shops are studied for performance tracking. As a result of study differences between individual solutions and integrated solutions was revealed. It is found that integrating these functions are advantageous in terms of total performance measure, and thus customer satisfaction. Random search is better than ordinary solutions. On the other hand, semi-tabu, evolutionary strategies and their hybrids are outperformed random search. Hybrid search methods are found promising.

Keywords: Process planning, weighted due-date assignment, weighted scheduling, random search, hybrid evolutionary strategies, hybrid semi-tabu search.

Teslim Tarihi Anlaşmalı Entegre Süreç Planlama ve Çizelgeleme için Tabu Arama ve Hibrit Evrimsel Stratejiler Algoritmaları

Öz
İmalatın, süreç planlama, çizelgeleme ve teslim tarihinin belirlenmesi olmak üzere üç önemli fonksiyonu bulunmaktadır. Bu fonksiyonları ayrı ayrı gerçekleştirmek yerine, üçünü birlikte değerlendirmek daha gerçekçi ve uygulanabilir planların hazırlanmasına yardımcı olacaktır. Bu problemin çözümünde rassal arama, kısmi tabu, rassal arama/kısmi tabu hibriti, evrimsel stratejiler ve rassal arama/evrimsel stratejiler hibriti yöntemleri kullanılmıştır. Yöntemlerin performansını değerlendirmek amacıyla farklı büyüklükteki atölyeler üzerinde çalışılmıştır. Çalışma sonucunda ayrık çözümler ile entegre çözümler arasındaki farklar ortaya çıkmıştır. Bu fonksiyonların entegrasyonunun toplam performans açısından ve dolayısıyla müşteri memnuniyeti açısından avantajlı olduğu bulunmuştur. Rassal aramanın sıradan çözümlerden daha iyi olduğu görülmüştür. Öte yandan, kısmi tabu, evrimsel stratejiler ve bunların melezleri rassal aramadan daha iyi performans göstermektedir. Hibrit arama yöntemlerinin gelecek vadettiği görülmüştür.

Anahtar Kelimeler: Süreç planlama, ağırlıklı teslim tarihi ataması, ağırlıklı çizelgeleme, rassal arama, hibrit evrimsel stratejiler, hibrit kısmi tabu arama.

1. Introduction

Process planning, scheduling and due date assignment are three essential manufacturing functions in a job shop. Job shop scheduling is one of main production types and problem we studied should be considered seriously. Although classically these three functions are treated separately, lately numerous works are done on Integrated Process Planning and Scheduling

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Recieved : 9 July 2020
Revision : 5 January 2021
Accepted : 11 January 2021

(IPPS) and Scheduling with Due-date Agreement (SWDDA). Even though there are numerous works on some level of integration, unfortunately there are only a few works on IPPSDDA (Integrated Process Planning, Scheduling and Due-date Assignment) which fully integrates these three functions.

Since these three functions highly affect each other, it is better to integrate them as much as possible. Output of these functions are inputs to the downstream functions. For example, output of process planning becomes input for scheduling. Poor process plans cause poor scheduling performance. If there is no integration, process planner may always select some desired machines repeatedly and they may not select some undesired machines. This causes unbalanced machine loading and reduce shop floor performance. If due dates are given independently, then it may be unrealistic. We may give far due dates unnecessarily and this increase weighted earliness and due date costs. On the other hand, if we give too close due dates then we may not keep our promise and weighted tardiness cost increases. At the literature due dates are given disregarding the importance of customers, but in this study weight of each customer is considered.

In the literature some works punished tardiness, some punished earliness and tardiness, some punished maximum absolute lateness, and some punished number of tardy jobs etc. But in this research, we penalized sum of weighted tardiness, earliness, and due date related costs. These terms are penalized because we wanted to give realistic due dates and we penalized weighted due dates to prevent unnecessary far due dates especially for important customers. Far due date means loss of customer goodwill, loss of customer or price reduction. Weighted Tardiness is penalized to prevent late delivery. Similarly, to due date related cost, tardiness means customer ill will, loss of customer, loos of good reputation and price reduction. Classically only tardiness is punished but in JIT environment and in reality, earliness is also problem. Stock holding, storage and spoilage costs can be earliness costs. So weighted earliness is also punished in this study.

Only scheduling function is NP-Hard class problem. So integrated problem is even harder to solve. As we mentioned earlier there are not much work on IPPSDDA. For the problems on IPPS and on SWDDA exact solutions are tried for very small problems. But for large problems only some good heuristics are advisable. In this research we applied evolutionary strategies, semi-tabu, random, hybrid evolutionary strategies and hybrid tabu search techniques are applied in the solution of the problem.

We represented problem as chromosomes with (n+2) genes where n represent number of the jobs. First two genes are used to represent due date assignment rule and dispatching rule sequentially. Remaining genes are used to represent currently selected route of each job. As we mentioned five search techniques are used and compared with one another. Hybrid Evolutionary strategies is found best among all others.

Eight shop floors are tested, and characteristics of these shop floors are given at section 3.

We also tested different integration levels and tested the benefit of higher integration levels. Firstly, we tested unintegrated case where process plans are selected randomly, jobs are scheduled in random order and due dates are assigned randomly (externally). Later we integrated Weighted Minimum Slack (WMS) dispatching with process plan selection. After that we tested integration of Weighted Slack (WSLK) due date assignment with process plan selection. Finally, we integrated three functions and we tested integration of process planning with WMS dispatching and WSLK due date assignment. As we mentioned weighted due date assignment with weighted scheduling and process plan selection is not addressed at the literature but in this study, we tried to prove benefit of integration with weighted scheduling and weighted due date assignment.

Process planning is defined as the systematic determination of the methods by which a product is to be manufactured economically and competitively according to Society of Manufacturing Engineers.

Zhang and Mallur (1994) defined production scheduling as a resource allocator, that considers timing data while allocating resources to the tasks.

Pinedo and Chao (1998) defined the job shop-scheduling environment as; n jobs to be processed and m machines to process these jobs. Each job follows some predetermined routes, visiting a number of machines. Job shop problems occur primarily in industries where each customer order has specified characteristics and order sizes are moderately small.

Gordon et al. (2002) presented a good literature survey on SWDDA. According to Gordon et al. (2002) the scheduling problems involving due dates are of essential concern. In a conventional production environment, a job is expected to be completed before its due date. In a just-in-time environment, a job is required to be finished precisely at its due date.

If we look at more recent works, we see SWDWA (Scheduling with Due-window Assignment) problem became very popular in place of SWDDA problems. Here due window is tried to be assigned instead of due date. In this problem most suitable window with starting point and length is tried to be determined.

Development in hardware, software and algorithm makes it possible to solve new problems or to solve old problem easier which were hard to solve previously. After recent development in computer it is possible to develop process plans easier. CAPP (Computer Aided Process Planning) became possible and we can prepare process plan faster. Since process planning easier, we can prepare alternative process plans which help to balance shop floor and increase shop floor utilization.

Since we minimize weighted due date, earliness, and tardiness we should better schedule important customers earlier. If we give close due dates for important customers at the beginning and schedule these customers earlier then there can be substantial improvements in performance measure and reduction in overall weighted cost. This is tried to be observed in this research.

It is important to solve problem in a reasonable amount of time otherwise solution would be practically useless. For this reason, we applied Evolutionary Strategies (ES), Semi-Tabu Search (ST), RS/ES hybrid, RS/ST hybrid and Random Search (RS) metaheuristics to find a good solution in an acceptable amount of time. We also compared search results with initial Ordinary Solutions (OS) solutions and proved searches are very useful. As expected, directed searches (ES, ST) and semi-directed searches (RS/ES, RS/ST) outperformed undirected (RS) search.

After representing problem as chromosome, we gave higher probability for first two genes to be selected for mutation operator. Because changes in these genes greatly affect solution compared to slow effect of a route of a single job. So, we applied dominant genes and found it useful.

We penalized weighted tardiness, earliness, and due dates. This penalty function is found to be realistic and very useful for IPPSDDA problem. These three terms in penalty function are all undesired. Tardiness is punished more according to earliness in terms of fixed and variable cost. These cost terms and penalty function are explained at section 3.

In short as integration level increased solution became better. Searches are found very useful and RS/ES outperformed all others. Best combination is observed where full integration with RS/ES is used. Using weighed due date assignment and weighted dispatching are found useful and dominant genes are used and this was also very helpful. In contrast to literature we penalized three terms which are weighted tardiness, earliness and due dates which is better and more realistic.

2. Background and literature survey

Although IPPS and SWDDA are both popular research topics, IPPSDDA are quite novel and only a few researches were made. If we look at the recent decade numerous works are conducted on IPPS. Traditionally three functions are applied sequentially and separately. Before going into detail, it is better to see recent surveys on IPPS. Tan and Khoshnevis (2000) and Phanden et al. (2011) prepared surveys on IPPS. For the SWDDA problem it is better to review survey of Gordon et al. (2002). For the IPPSDDA problem it is better to see Demir and Taskin (2005) and Ceven and Demir (2007). Demir and Taskin (2005) worked on IPPSDDA problem in a Ph.D. Thesis. Later Ceven and Demir (2007) worked on benefit of integrating due date assignment with IPPS problem in an M.S. Thesis.

If more literature is to be listed on IPPS problem we can give the following earlier works on this problem; Wilhelm and Shin (1985), Khoshnevis and Chen (1991), Zhang and Mallur (1994), Usher and Fernandes (1996), Brandimarte (1999), Weintraub et al. (1999), Morad and Zalzala (1999), Gindy et al. (1999).

If we integrate process plan selection with scheduling, then we should determine alternative process plans and number of alternative process plans wisely. Corti and Portioli-Staudacher (2004) studied alternative process plans availability and their effect on manufacturing system performance.

It is difficult to select best plans if there are multiple process plans. Ming and Mak (2000) studied process plan selection problem by using a hybrid Hopfield network-genetic algorithm. Bhaskaran (1990) studied process plan selection in his study.

Developments in hardware, software and algorithms provide us to solve the problems which could not be solved earlier, or we can solve the problems easier. Recent developments provide CAPP (Computer aided process planning). Usher and Fernandes (1996) and Aldakhilallah and Ramesh (1999) studied integration of process planning with CAPP.

IPPS problem is an NP-hard problem and researchers commonly uses metaheuristics such as genetic or evolutionary algorithms. Morad and Zalzala (1999), Moon et al. (2002), Kim et al. (2003), Drstvenšek and Balič (2003), Moon et al. (2008), Seker et al. (2013), Zhang and Wong (2015) are worked on this problem. Following works are relatively more recent works on IPPS; Ming and Mak (2000), Tan and Khoshnevis (2000), Thomalla (2001), Kim et al. (2003), Usher (2003), Drstvenšek and Balič (2003), Corti and Portioli-Staudacher (2004), Shrestha et al. (2008), Moon et al. (2008), Özgüven et al. (2010), Leung et al. (2010), Phanden et al. (2011), Li et al. (2012), Seker et al. (2013), Zhang and Wong (2015), Petrović et al. (2016), and Zhang et al. (2016).

As in IPPS there are hundreds of works on SWDDA. As it is mentioned earlier before going into detail of SWDDA it is better to see Gordon et al. (2002) as a state of the art survey on scheduling with common due date assignment.

Classically tardiness is tried to be penalized but according to JIT (Just in Time) philosophy we should penalize both earliness and tardiness. Since nobody prefer long due dates in this study all of weighted earliness, tardiness and due date related costs are tried to be minimized.

Due dates can be determined internally or externally. At the latter case we try to catch best performance according to externally dictated due dates. But at the former case we try to assign best due dates for the jobs that serve most to the benefit of the firm. For this reason, SWDDA problem gained importance as research topic and many works are conducted on this problem. If we look at the earlier works on SWDDA problem we can see the following works; Luss and Rosenwein (1993), Yang et al. (1994), Lawrence (1994), Cai et al. (1997), Kovalyov (1997), Gordon and Kubiak (1998), Cheng and Kovalyov (1999), Gordon and Strusevich (1999).

Some of the recent works on SWDDA can be given as follows; Biskup and Jahnke (2001), Mosheiov (2001), Gordon et al. (2002), Birman and Mosheiov (2004), Lauff and Werner (2004), Baykasoğlu et al. (2008), Gordon and Strusevich (2009), Allaoua and Osmane (2010), Tuong and Soukhal (2010), Li et al. (2011),Vinod and Sridharan (2011), Shabtay (2016), and Koulamas (2017).

We can assign common and separate due dates for every job. If we solve job shop scheduling problem, we may assign separate due dates but in case of assembly and simultaneous delivery cases we may assign common due dates for the jobs to be scheduled. Many works in the literature are on scheduling with common due date assignment (SWCDDA) such as Chen et al. (1997), Kovalyov (1997), Biskup and Jahnke (2001), Mosheiov (2001), Gordon et al. (2002), Gordon and Strusevich (2009), Allaoua and Osmane (2010), Tuong and Soukhal (2010), and Li et al. (2011).

Unlike SWCDDA some works are on SWSDDA (Scheduling with separate due date assignment) such as Gordon and Kubiak (1998), Cheng and Kovalyov (1999), Gordon and Strusevich (1999), Baykasoğlu et al. (2008), Gordon and Strusevich (2009), Li et al. (2011), Vinod and Sridharan (2011). In this study every job gets its own due date.

Some of these studies have single, some double, and some have multiple machines. As an example to SMSWDDA (Single machine scheduling with due date assignment) following works can be given: Cai et al. (1997), Kovalyov (1997), Gordon and Strusevich (1999), Gordon et al. (2002), Gordon and Strusevich (2009), Allaoua and Osmane (2010), Tuong and Soukhal (2010), Li et al. (2011).

Birman and Mosheiov (2004) studied two machine flow shop scheduling with due date determination (TMFSWDDA).

Following works are on PMSWDDA (Parallel machine scheduling with due date assignment); Cheng and Kovalyov (1999), Gordon et al. (2002), and Tuong and Soukhal (2010).

Following works are on MMSWDDA (Multi machine scheduling with due date assignment); Luss and Rosenwein (1993), Lawrence (1994), and Lauff and Werner (2004).

Some works are on JSSWDDA (Job shop scheduling with due date assignment) such as Yang et al. (1994), Baykasoğlu et al. (2008), and Vinod and Sridharan (2011). In this study jobs are tried to be assigned separate due dates and every shop floor tested as a case of job shop with different sizes.

One of the current study areas is the dynamic scheduling problem. There are a limited number of studies in the literature on the dynamic integrated process planning, scheduling, and due date assignment (DIPPSDDA). Demir and Erden (2020) tried to optimize the dynamic environment with ant colony algorithm in their work. DIPPSDDA, which was previously improved with the genetic algorithm and some meta-heuristic algorithms (Erden et al., 2019), was a new field of study.

3. Problem definition

As we mentioned earlier IPPS and SWDDA problems are studied extensively. In this research we studied IPPSDDA problem. We have three functions to be integrated which are process planning, scheduling, and due date assignment. Step by step we integrated these functions with each other and tried to see benefit of integration level. Problem is represented as chromosomes which have (n+2) genes where n is the number of jobs. First two genes are used to represent due date assignment and dispatching rule genes. There are two different due date assignments and four different dispatching rules. Mainly, we used WSLK weighted due date assignment rule and RDM (Random) due date assignment rule. At dispatching gene, we used WMS and SIRO (Service in Random Order) rules, so we have two dispatching rules to choose from.

We studied eight different shop floors with varying size. There are five different routes to choose from for each job in smaller shop floors. At the smallest shop floor, we have 5 machines, 25 jobs and 5 routes. There are 10 operations in each route. Processing time of each operation practically changes in between 1 and 30 minutes according to formula $\lfloor(12 + \mathrm{z} * 6)\rfloor$ where z is the standard normal numbers in which $\sigma = 6$ and $\mu = 12$.

At the largest shop floor, we have 40 machines, 200 jobs, 3 routes and there are 10 operations in each route. Processing times are same as in other shop floors. We took 3 alternative routes in larger shop floors to find a solution in a reasonable amount of time. Characteristics of each shop floors are listed at Table 1.

Table 1. Shop floors

Shop Floor	1	2	3	4	5	6	7	8
# of machines	5	10	15	20	25	30	35	40
# of Jobs	25	50	75	100	125	150	175	200
# of Routes	5	5	5	5	3	3	3	3
Processing Times	$\lfloor(12 + \mathrm{z} * 6)\rfloor$							
# of op. per job	10							

We started from unintegrated version of the problem where process plan selection is made independently, due dates are determined randomly (externally) and jobs are dispatched randomly. Later WMS rule is integrated with process plan selection, but due dates are still determined randomly. After that we integrated WSLK due date assignment with process plan selection, but jobs are scheduled according to SIRO rule.

At the end we integrated all of the three functions. Process plan selection is performed with WMS dispatching and WSLK due date assignment. We found this case as the best. General flow diagram is given in Figure 1.

We assumed a working day as one shift which is 8 hours or 480 minutes. As a performance measure we tried to minimize weighted tardiness, earliness and due date related costs. We penalized these terms proportional with the weights of the customers and proportional to the tardiness, earliness and due dates multiplied with different constants. For tardiness and earliness, we also used fixed cost if there is tardiness or earliness. Penalty function for each term is given below where PD is penalty for due-date (Equation 1), PE is penalty for earliness (Equation 2), PT is penalty for tardiness (Equation 3), Penalty of a job is Penalty(j) (Equation 4) and Total penalty (Equation 5).

$$PD = weightj * 8 * (DueDate/480) \qquad (1)$$

$$PE = weight\ (j) * (5 + 4 * (E/480)) \qquad (2)$$

$$PT = weight\ (j) * (10 + 12 * (T/480)) \qquad (3)$$

$$Pen(j) = PD + PE + PT \qquad (4)$$

$$Total\ Penalty = jPen(j) \qquad (5)$$

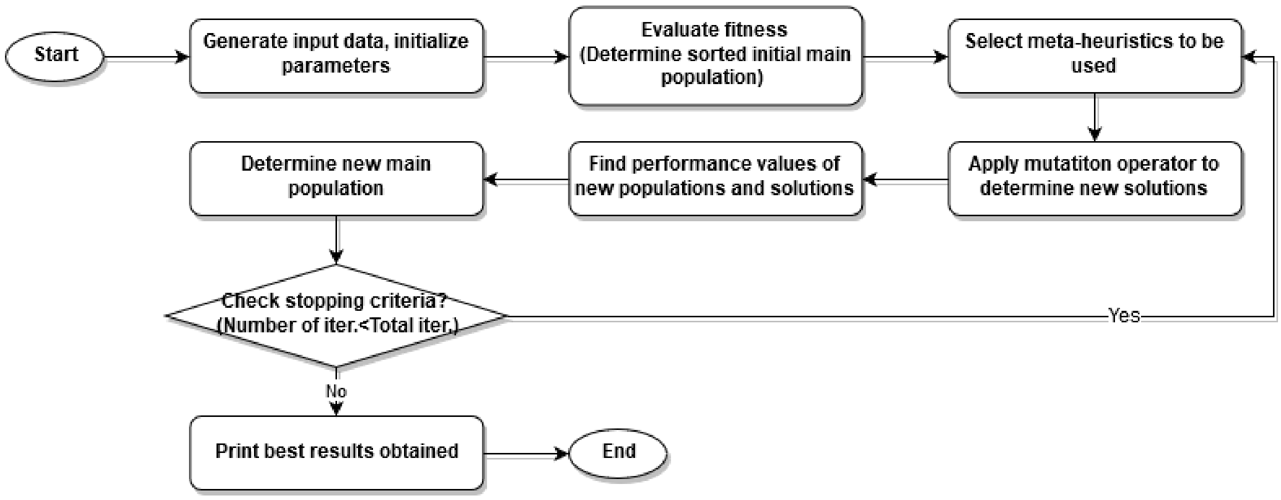

Figure 1. General flow diagram

4. Solution techniques

We used initially randomly produced chromosome as the ordinary solution and compared this result with the results of evolutionary strategies, semi-tabu search, hybrid searches and random search results.

Scheduling problem alone belongs to NP-Hard problem and integrated problem is even harder to solve that is why some good heuristics are required to solve this problem in a reasonable amount of time. We applied pure, hybrid and random searches because of the characteristics of the problem. Each solution type is explained below.

Ordinary Solution (OS): OS is the initially randomly produced chromosome which represent any random chromosome possible at the beginning and as expected it is the poorest solution compared to the pure, hybrid and random search metaheuristics.

Random Search (RS): Here only RS is applied, and always brand-new solutions are produced randomly. To be fair with other search techniques same number of chromosomes are produced in each iteration as in other pure and hybrid metaheuristics. We applied 200, 150, 100 and 50 random iterations for eight shop floors in doubles, respectively. At each iteration we produced 10 new random chromosomes. Later we took best 10 chromosomes from previous main population and newly produced 10 chromosomes. Random search is found very useful compared to ordinary solutions and marginal improvements are very high at the very beginning of the search, but marginal improvement reduces sharply as iteration goes on. That is why random search is poor compared to the other metaheuristics. Hybrid searches are powerful with the combination of high marginal improvement of RS at the beginning and good search characteristics of the directed searches later on.

Evolutionary Strategies (ES): During 1960s Rechenberg (1965), and Schwefel (1981) two students of Technical University of Berlin, Germany, developed ES to solve optimization problem. Main difference between ES and Genetic Algorithm (GA) is the operators used. While ES uses only mutation operator, GA uses both mutation and crossover operators. We produce ten new chromosomes by applying mutation operator in each iteration. ES flow diagram is given in Figure 2.

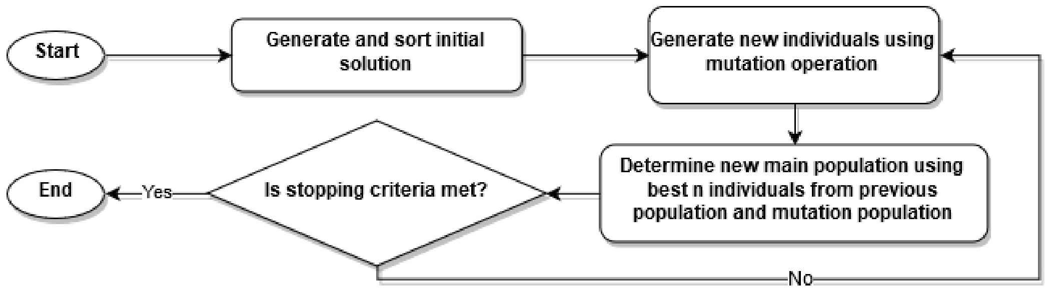

Figure 2. Evolutionary strategies flow diagram

Semi-Tabu Search (ST): For a shop floor which consists of 200 jobs, there are 202 genes and totally 4x2x3200 = 2.1249119e+96 combinations are possible. If we list every gene in tabu list, then problem becomes too complex to consider. Instead, we list only dominant genes in tabu list and apply mutation operator for remaining genes as given in Figure 3. Unlike ES we work on a single chromosome in every iteration, so we applied 10 times more iterations in this metaheuristic to be fair in comparison with ES.

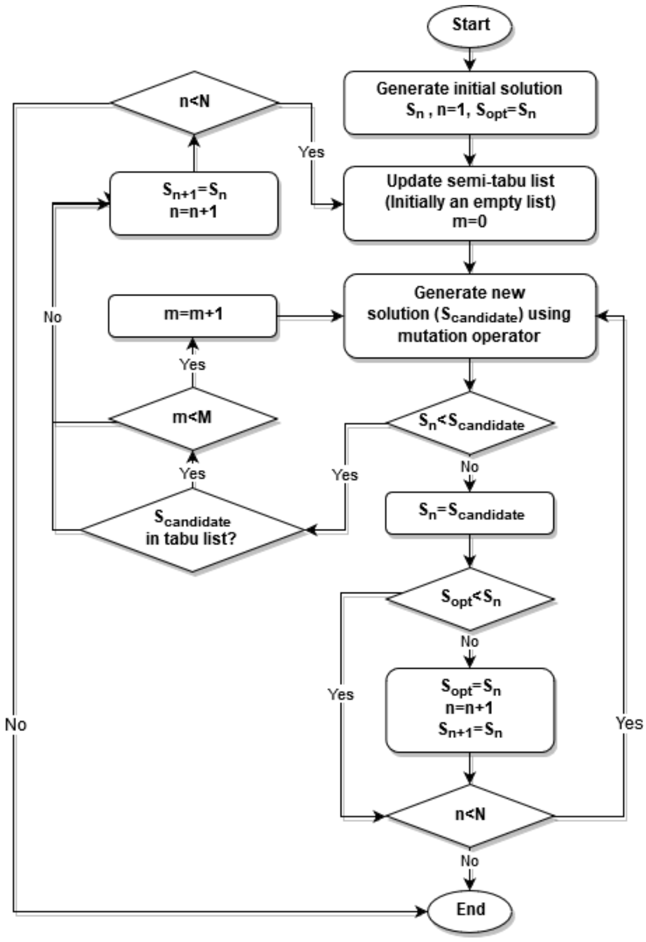

Figure 3. Semi-tabu search flow diagram

Terms used in Figure 3 is defined as follows:

S_n : nth iteration solution

$S_{candidate}$: candidate solution

S_{opt} : optimum solution

N : total iteration number (stopping criterion)

n : current iteration number

m : current trial number in tabu list

M : Number of allowed trials in tabu list

Hybrid Evolutionary Strategies (RS/ES): This is a hybrid metaheuristic and initially at the first 5% of the iterations RS is applied and ES is applied to remaining 95% of the iterations. If a random number is generated between 0 and 1000 then expected value of the minimum is 500. If we generate two random numbers and take the minimum, then we get expected value of 330. If we generate three random numbers and take the minimum of these the expected value, we get is 250. Now if we look at marginal improvements, we get 500, 170 and 80, respectively. So, it is obvious that initial random iterations are very useful but marginal improvements reduces sharply. So here we started with RS and later we continued with ES. Since marginal benefits reduce sharply RS rate should be low and we applied 5% RS iterations.

Hybrid Semi-Tabu Search (RS/ST): Here again initially 5% RS is applied and later 95% ST search is applied. We used dominant genes in ES, ST, RS/ES and RS/ST while applying mutation operator. First two genes are dominant and that is why they had more probability to be selected for mutation. Using dominant genes improved efficiency of solution technique. While running program we recorded CPU times required. These times are listed at the Table 4 given at section 6.

As mentioned earlier, problem is represented as a chromosome with n+2 genes where n is the number of jobs. First two genes are used to represent due date assignment and dispatching rules, respectively. Remaining genes represent active selected route of each job. A sample chromosome is given at Figure 4.

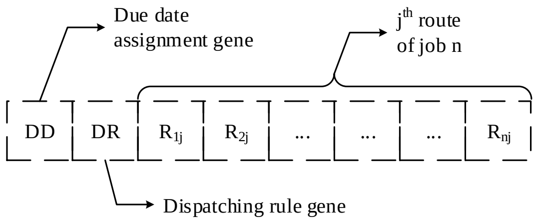

Figure 4. Sample chromosome

5. Experimentation

Mainly two types of due date assignment rules are used. With different constants first gene takes one of four different values. Mainly WSLK and RDM due date assignment rules are used. At the first rule, which is WSLK, some constant added to total processing time of each job according to weight of that job. At the RDM due date assignment, due dates are determined randomly as explained at Appendix 1. Rules are listed at Table 2. At the second gene we used two dispatching rules which are WMS and SIRO. These rules are listed at Table 3 and explained at Appendix.

Table 2. Due-date assignment rules

Method	Constant q_x	Rule no
WSLK	$q_x = q_1,q_2,q_3$	1,2,3
RDM		4

Table 3. Dispatching rules

Method	Rule No
WMS	1
SIRO	2

We used a desktop computer with 3.1 GHz Intel i5-2400 processor and 4 GB ram with 64-bit Windows 10 operating system to run the program. We used Borland C++ 5.02 compiler. CPU Times are listed at Table 4. Screenshot of the program is given in Figure 5 and Figure 6.

```
F:\2-1-AHK-2-2-WMS-WSLK-REVISE\1-25-5-5>1-4-WMS-WSLK-es-mix 2048
Random number generator seed= 2048
Population (10 chromosomes) :
           PERF DD DR J0---->Rest of the jobs
Row  0 :  294.91  3  6  0 0 1 4 2 3 2 0 0 2 4 2 4 3 2 3 4 2 3 2 1 0 1 0 3
Row  1 :  301.77  3  6  0 2 0 1 0 0 2 0 4 2 3 3 1 1 2 1 3 3 1 0 0 1 1 2 4
Row  2 :  303.43  3  6  1 3 2 2 2 2 0 0 0 3 0 4 3 1 2 1 2 4 1 4 2 0 0 0 0
Row  3 :  304.75  3  6  3 3 4 2 3 3 1 4 3 1 2 0 1 0 3 3 0 3 2 3 0 1 1 0 0
Row  4 :  311.14  4  6  1 0 1 4 4 2 4 4 3 0 2 1 0 1 4 0 1 2 0 4 3 4 4 2 2
Row  5 :  330.80  4  6  4 3 3 1 1 4 3 4 4 2 1 2 0 4 0 3 2 3 2 4 3 1 0 2 0
Row  6 :  341.78  5  6  1 2 2 0 4 1 4 2 2 0 4 3 3 2 3 1 2 0 4 4 0 4 1 2 2
Row  7 :  344.35  5  6  0 2 2 3 1 0 2 0 0 2 0 1 1 4 2 0 3 4 2 1 0 2 1 3 0
Row  8 :  355.04  5  6  3 3 3 2 3 2 1 1 4 3 1 0 0 2 3 4 4 2 1 3 4 4 2 0 2
Row  9 :  362.65  5  6  3 2 2 1 3 3 4 3 0 3 1 4 1 1 3 2 0 4 1 2 3 0 3 3 4
```

Figure 5. Screenshot of the program start

We tested eight shop floors and certain number of iterations are applied for each shop floor. To be fair, same number of iterations are applied for both evolutionary search and random search. Since at the ES and RS, we produce 10 chromosomes and in ST we produce only one new chromosome thus we executed 10 times more iterations compared to the ES and RS. 200 iterations are applied for the smallest shop floors which are SF1 (Shop Floor 1) and SF2. For SF3 and SF4 we applied 150 iterations. For SF5 and SF6 we used 100 iterations and finally for the largest two shop floors which are SF7 and SF8 we applied 50 iterations.

```
Iteration 200
           PERF DD DR J0---->Rest of the jobs
Row  0 :  265.10  3  6  0 1 3 1 0 3 3 4 0 1 0 0 1 3 4 0 2 1 3 4 4 4 3 2 3
Row  1 :  266.53  3  6  0 1 1 1 0 0 4 1 0 4 0 0 1 3 1 1 2 2 3 0 1 4 2 2 3
Row  2 :  266.54  3  6  0 1 3 1 0 3 3 0 0 1 0 4 1 3 1 0 2 1 3 4 4 4 3 2 3
Row  3 :  266.57  3  6  2 1 1 1 0 2 4 1 0 4 0 2 1 2 0 4 0 0 3 0 1 4 1 4 3
Row  4 :  266.99  3  6  0 1 3 1 0 3 3 4 0 1 0 0 1 1 4 0 2 1 3 3 4 4 3 4 3
Row  5 :  267.36  3  6  2 1 2 0 0 2 4 1 0 0 0 3 1 3 2 0 2 0 3 0 1 4 2 4 2
Row  6 :  267.63  3  6  2 1 1 0 0 2 4 1 0 4 0 0 1 0 0 0 2 1 3 2 1 4 2 4 2
Row  7 :  267.68  3  6  2 1 1 1 0 2 4 1 0 4 0 2 1 2 0 0 2 0 3 0 1 4 2 4 3
Row  8 :  267.74  3  6  2 1 2 0 0 2 4 1 0 4 0 3 1 2 0 0 2 0 3 0 1 4 2 4 2
Row  9 :  267.84  3  6  2 1 1 3 0 2 4 1 0 0 0 3 1 2 3 0 2 1 3 0 1 4 2 4 2

Best: 265.10    Average: 267.00    Worst: 267.84
200 iterations are applied before stopping.


Results obtained in last iteration

Best performance                    : 265.10
Best due-date assignment rule       : 3
Best dispatching rule               : 6

Best route for job 0                : 0
Best route for job 1                : 1
Best route for job 2                : 3
Best route for job 3                : 1
Best route for job 4                : 0
Best route for job 5                : 3
Best route for job 6                : 3
Best route for job 7                : 4
Best route for job 8                : 0
Best route for job 9                : 1
Best route for job 10               : 0
Best route for job 11               : 0
Best route for job 12               : 1
Best route for job 13               : 3
Best route for job 14               : 4
Best route for job 15               : 0
Best route for job 16               : 2
Best route for job 17               : 1
Best route for job 18               : 3
Best route for job 19               : 4
Best route for job 20               : 4
Best route for job 21               : 4
Best route for job 22               : 3
Best route for job 23               : 2
Best route for job 24               : 3

Cpu time                            : 18.88 sec
Program execution time              : 19 sec
```

Figure 6. Screenshot of the program results

If we look at the approximate CPU times for every shop floor from the tables mentioned above; for the small shop floor, it took approximately between 16 and 88 seconds CPU time. For the small-medium shop floor, it took approximately between 173 and 322 seconds. For the medium-large shop floor, it took approximately between 257 and 376 seconds and for the largest shop floor, it took between 250 and 346 seconds. CPU time of the largest shop floor is lower than the medium-large shop floor due to its iteration number.

SIRO-RDM (OS, RS, ES, ST, RS/ES, RS/ST), WMS-RDM (OS, RS, ES, ST, RS/ES, RS/ST), SIRO-WSLK (OS, RS, ES, ST, RS/ES, RS/ST), and WMS-WSLK (OS, RS, ES, ST, RS/ES, RS/ST) are the twenty-four solutions, we compared in this study. Initially, we tested SIRO-RDM combinations. Here three functions are unintegrated. Later we tested WMS-RDM combinations in which WMS scheduling is integrated with process plan selection and due-dates are determined randomly. After that, we tested SIRO-WSLK combinations. Now WSLK due-date assignment is integrated with process planning but now jobs are scheduled in random order. Later we tested all combinations at the fully integrated level which are

WMS-WSLK combinations. According to results, full integration with RS/ES found as the best solution. Searches are found always better compared to ordinary solutions and RS. Obtained results are explained in the conclusion section.

We tested eight shop floors for twenty-four different solutions. Shop floor characteristics and twenty-four types of solutions are explained in the previous sections of the study. At every shop floor, operation times are determined randomly according to the formula $\lfloor(12 + z * 6)\rfloor$ where z is the standard normal numbers.

In first small shop floor (SF-1) there are 25 jobs and 5 machines. For this shop floor, we applied 200 iterations for ES and RS, 2000 iterations for ST which took 16 seconds on average. Smallest shop floor results are given in **Hata! Başvuru kaynağı bulunamadı.**.

In second small shop floor (SF-2) there are 50 jobs and 10 machines. For this shop floor, we applied 200 iterations for ES and RS, 2000 iterations for ST which took 88 seconds on average. Second smallest shop floor results are given in **Hata! Başvuru kaynağı bulunamadı.**.

In first small-medium shop floor (SF-3) there are 75 jobs 15 machines. For this shop floor, we applied 150 iterations for ES and RS, 1500 iterations for ST which took 173 seconds on average. First small-medium shop floor results are given in **Hata! Başvuru kaynağı bulunamadı.**.

In second small-medium shop floor (SF-4) there are 100 jobs 20 machines. For this shop floor, we applied 150 iterations for ES and RS, 1500 iterations for ST which took 321 seconds on average. Second small-medium shop floor results are given in **Hata! Başvuru kaynağı bulunamadı.**.

In first medium-large shop floor (SF-5) there are 125 jobs 25 machines. For this shop floor, we applied 100 iterations for ES and RS, 1000 iterations for ST which took 256 seconds on average. First medium-large shop floor results are given in Figure 11.

In second medium-large shop floor (SF-6) there are 150 jobs 30 machines. For this shop floor, we applied 100 iterations for ES and RS, 1000 iterations for ST which took 376 seconds on average. Second medium-large shop floor results are given in Figure 12.

In first largest shop floor (SF-7) we have 175 jobs to be scheduled and 35 machines on this shop floor. We applied 50 iterations for ES and RS, 500 iterations for ST which took 250 seconds on average. First largest shop floor results are given in Figure 13.

For the largest shop floor (SF-8) we have 200 jobs to be scheduled and 40 machines on this shop floor. We applied 50 iterations for ES and RS, 500 iterations for ST which took 346 seconds on average. Second largest shop floor results are given in Figure 14.

According to results, we found similar conclusions. Higher integration gave better results and full integration was the best. Searches are found superior to ordinary and RS solutions. Full integration with RS/ES gave the best results. Comparisons of twenty-four solution combinations for all the shop floors are given in Table 4. Best solution found in a level is indicated with bold text, for each shop floor. Best of all levels (24 solutions) are indicated with green bold text, for each shop floor.

Figure 7. Results of Shop Floor 1 (25x5x5)

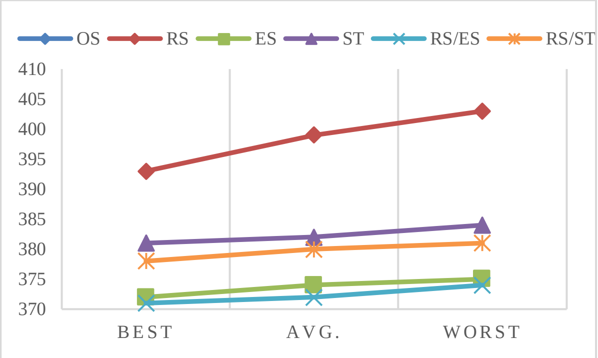

Figure 8. Results of Shop Floor 2 (50x10x5)

Figure 9. Results of Shop Floor 3 (75x15x5)

Figure 10. Results of Shop Floor 4 (100x20x5)

Table 4 Comparison of twenty-four solution combinations for all of the shop floors

Level	Approach	Shop Floor 1					Shop Floor 2					Shop Floor 3					Shop Floor 4			
		Best	Avg.	Worst	CPU		Best	Avg.	Worst	CPU		Best	Avg.	Worst	CPU		Best	Avg.	Worst	CPU
SIRO-RDM	OS	319	319	319	-	OS	646	646	646	-	OS	983	983	983	-	OS	1309	1309	1309	-
	RS	265	272	276	17	RS	586	598	606	88	RS	853	895	908	179	RS	1269	1278	1285	331
	ES	246	252	254	15	ES	546	552	556	84	ES	833	842	846	176	ES	1197	1204	1210	311
	ST	252	255	256	14	ST	554	562	565	79	ST	**829**	841	848	162	ST	1234	1246	1254	299
	RS/ES	**240**	248	251	15	RS/ES	**545**	548	551	84	RS/ES	831	836	842	174	RS/ES	**1207**	1216	1222	312
	RS/ST	267	268	270	15	RS/ST	557	570	574	82	RS/ST	847	862	868	167	RS/ST	1219	1230	1238	297
WMS-RDM	OS	270	270	270	-	OS	564	564	564	-	OS	817	817	817	-	OS	1184	1184	1184	-
	RS	230	236	239	15	RS	520	528	532	88	RS	770	782	787	182	RS	1121	1139	1150	333
	ES	201	205	208	14	ES	**459**	465	469	83	ES	**700**	706	713	172	ES	**1058**	1069	1075	306
	ST	208	213	216	13	ST	494	501	505	79	ST	738	745	748	162	ST	1092	1099	1104	286
	RS/ES	**195**	201	203	16	RS/ES	467	475	481	82	RS/ES	729	734	735	171	RS/ES	1061	1068	1073	306
	RS/ST	196	205	210	13	RS/ST	485	489	493	80	RS/ST	731	739	744	163	RS/ST	1088	1096	1101	294
SIRO-WSLK	OS	314	314	314	-	OS	666	666	666	-	OS	997	997	997	-	OS	1372	1372	1372	-
	RS	263	272	279	16	RS	571	588	596	94	RS	861	883	893	176	RS	1204	1222	1232	343
	ES	**248**	255	257	16	ES	530	548	551	95	ES	812	824	831	170	ES	**1130**	1153	1160	331
	ST	**248**	257	263	15	ST	544	557	563	87	ST	854	861	867	161	ST	1186	1200	1206	313
	RS/ES	249	256	259	16	RS/ES	**529**	538	545	86	RS/ES	**804**	817	824	174	RS/ES	1138	1167	1178	333
	RS/ST	261	265	268	15	RS/ST	541	549	553	86	RS/ST	833	847	850	162	RS/ST	1187	1195	1199	318
WMS-WSLK	OS	270	270	270	-	OS	533	533	533	-	OS	783	783	783	-	OS	1142	1142	1142	-
	RS	191	195	197	17	RS	393	399	403	97	RS	593	600	606	191	RS	912	930	938	368
	ES	**180**	181	182	17	ES	372	374	375	99	ES	566	568	570	185	ES	847	851	852	347
	ST	182	183	184	17	ST	381	382	384	94	ST	576	579	581	176	ST	862	873	879	333
	RS/ES	**180**	181	182	17	RS/ES	**371**	372	374	98	RS/ES	**564**	566	568	185	RS/ES	**844**	848	850	345
	RS/ST	181	182	183	17	RS/ST	378	380	381	90	RS/ST	577	580	582	177	RS/ST	859	868	872	332

Level	Approach	Shop Floor 5					Shop Floor 6					Shop Floor 7					Shop Floor 8			
		Best	Avg.	Worst	CPU		Best	Avg.	Worst	CPU		Best	Avg.	Worst	CPU		Best	Avg.	Worst	CPU
SIRO-RDM	OS	1831	1831	1831	-	OS	2110	2110	2110	-	OS	2154	2154	2154	-	OS	2783	2783	2783	-
	RS	1590	1632	1644	260	RS	1914	1930	1944	403	RS	2108	2154	2171	256	RS	2659	2707	2719	357
	ES	1556	1569	1577	251	ES	**1840**	1858	1867	386	ES	2067	2092	2101	248	ES	**2585**	2600	2606	341
	ST	1594	1608	1616	230	ST	1863	1875	1883	335	ST	2091	2103	2114	220	ST	2640	2654	2661	308
	RS/ES	**1538**	1558	1566	249	RS/ES	1860	1877	1884	391	RS/ES	**2060**	2085	2092	249	RS/ES	2624	2628	2635	344
	RS/ST	1555	1574	1581	226	RS/ST	1863	1881	1887	338	RS/ST	2112	2121	2128	223	RS/ST	2594	2613	2626	304
WMS-RDM	OS	1558	1558	1558	-	OS	1836	1836	1836	-	OS	1947	1947	1947	-	OS	2470	2470	2470	-
	RS	1402	1429	1441	268	RS	1708	1716	1723	393	RS	1915	1926	1938	262	RS	2412	2423	2431	368
	ES	1372	1377	1381	249	ES	**1633**	1636	1639	365	ES	1886	1896	1902	256	ES	2335	2346	2351	348
	ST	1374	1380	1386	233	ST	1662	1669	1675	342	ST	**1858**	1885	1892	224	ST	2344	2356	2362	315
	RS/ES	1371	1376	1378	254	RS/ES	1647	1652	1656	369	RS/ES	1867	1872	1877	249	RS/ES	**2332**	2343	2349	348
	RS/ST	**1366**	1375	1379	231	RS/ST	1653	1663	1668	338	RS/ST	1900	1904	1907	227	RS/ST	2354	2362	2371	316
SIRO-WSLK	OS	1921	1921	1921	-	OS	2196	2196	2196	-	OS	2252	2252	2252	-	OS	2840	2840	2840	-
	RS	1577	1603	1615	270	RS	1843	1851	1857	398	RS	2025	2066	2080	264	RS	2560	2589	2607	369
	ES	**1531**	1544	1552	264	ES	1797	1809	1814	390	ES	1984	1999	2011	260	ES	**2441**	2461	2473	353
	ST	1546	1566	1576	241	ST	1829	1849	1860	350	ST	2031	2045	2059	231	ST	2481	2499	2512	318
	RS/ES	**1531**	1540	1547	265	RS/ES	**1792**	1803	1812	387	RS/ES	1988	2007	2015	261	RS/ES	2477	2486	2491	358
	RS/ST	1556	1578	1588	239	RS/ST	1845	1854	1860	346	RS/ST	**1982**	2009	2026	231	RS/ST	2473	2519	2538	322
WMS-WSLK	OS	1538	1538	1538	-	OS	1801	1801	1801	-	OS	1791	1791	1791	-	OS	2348	2348	2348	-
	RS	1036	1083	1107	301	RS	1329	1359	1370	422	RS	1486	1497	1503	284	RS	1862	1911	1928	395
	ES	994	1001	1004	279	ES	1282	1286	1288	407	ES	**1457**	1462	1465	279	ES	1801	1812	1818	384
	ST	999	1017	1025	269	ST	1209	1216	1221	375	ST	1458	1467	1472	251	ST	1819	1835	1844	346
	RS/ES	**990**	998	1002	280	RS/ES	1274	1279	1282	406	RS/ES	**1457**	1462	1464	278	RS/ES	**1786**	1800	1807	381
	RS/ST	1006	1014	1021	269	RS/ST	**1206**	1215	1221	375	RS/ST	1460	1468	1473	251	RS/ST	1802	1823	1835	344

Figure 11. Results of Shop Floor 5 (125x25x3)

Figure 12. Results of Shop Floor 6 (150x30x3)

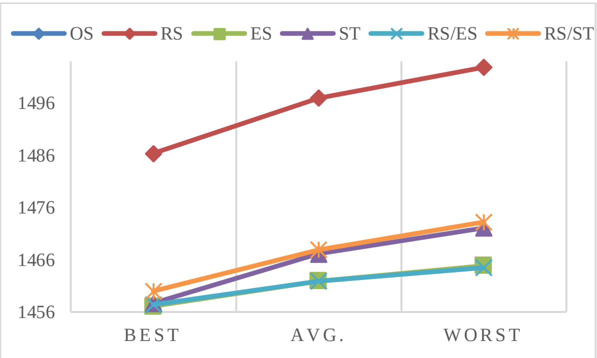

Figure 13. Results of Shop Floor 7 (175x35x3)

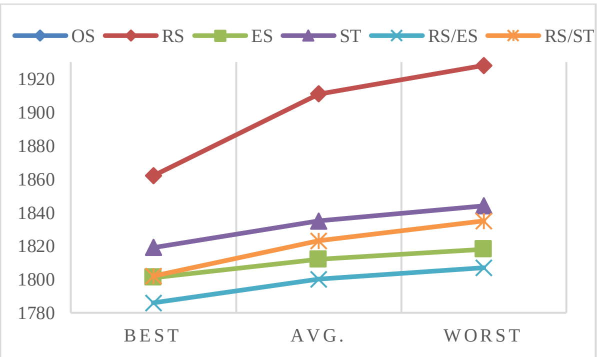

Figure 14. Results of Shop Floor 8 (200x40x3)

For each SIRO-RDM combination, a single experiment was performed, and RS/ES 4 (50%), ES 3 (37.5%), and ST 1 (12.5%) times gave the best results. For each WMS-RDM combination, a single experiment was performed and ES 4 (50%), RS/ES 2 (25%), RS/ST 1 (12.5%), and ST 1 (12.5%) times gave the best results. For each SIRO-WSLK combination, a single experiment was performed, and ES 4 (50%), RS/ES 3 (37.5%), and RS/ST 1 (12.5%) times gave the best results. For the WMS-WSLK combination, 5 experiments were conducted on each shop floor and totally 40 experiments were performed on 8 shop floors. RS/ES 19 (47.5%), ES 11 (27.5%), RS/ST 6 (15%), and ST 4 (10%) times gave the best results in these experiments.

When the best value of all combinations was considered, RS/ES 28 (43.75%), ES 22 (34.38%), RS/ST 8 (12.5%), and ST 6 (9.38%) times gave the best results in a total of 64 experiments. When the average value of all combinations was considered, RS/ES 34 (53.13%), ES 20 (31.25%), RS/ST 7 (10.94%), and ST 3 (4.69%) times gave the best results in a total of 64 experiments.

7. Conclusion

Production process takes place upon three functions, which are production planning, scheduling, and due-date assignment. Conventionally these three functions are executed separately in practice. On the other hand, these functions affect each other significantly as they are tightly connected with each other. These functions should be considered simultaneously to prepare more accurate production plans, schedules, and due-date assignments.

To be more realistic on due-date assignments weights are given to customers related to their relative importance for a company, and a penalty function is applied to optimize due-dates, in this study. As there will be times that all customers could not be satisfied at the same time. There will be a decision to be made in which customers will be delivered early, and which will be delivered late. Not only being late in production is a problem but also being early. As there will be stock holding costs etc.

Integration of three functions (IPPSDDA problem), which are mentioned above, are discussed in this study. Weighted scheduling and weighted due-date assignment are integrated with process plan selection. WMS is used as a dispatching rule and WSLK used as a due-date assignment rule. Studies made over IPPS, SWDDA, and IPPSDDA are surveyed and briefly given to comprehend the problem scope.

To present this idea and to explain the point of view clearly a problem set is generated. Shop floors with distinct characteristics in terms of machines, jobs, routes, and processing times are generated in order to evaluate the effectiveness and efficiency of the integration and the algorithms.

Evolutionary Strategies, Semi-Tabu Search and their hybrids with Random Search are used and compared with Random search, ordinary solution, and each other for all integration levels. Algorithms are provided with flow diagrams to better understand them.

Starting with unintegrated problem (SIRO-RDM) integration level is increased step by step to the fully integrated problem (WMS-WSLK) and the solution performance is observed with the above-mentioned algorithms. The best performance is obtained in the fully integrated level in most of the shop floors with RS/ES algorithm. In some of them, ES performs better than its hybrid.

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Appendix. Due-date assignment rules

$Due\ date = TPT + q_x \times k$

where

$q_x = q_1, q_2\ or\ q_3$
$q_1 = 0.5 \times P_{avg},$
$q_2 = P_{avg},$
$q_3 = 1.5 \times P_{avg}$

k is inversely determined according to the customer weights.

RDM (Random due assignment)
$Due\ = N \sim (3 \times P_{avg}\ , (P_{avg}\ )^2)$

TPT: total processing time

P_{avg}: mean processing time of all job waiting