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An hybrid SA-DATC Approach for JIT Open-Shop Scheduling Problem with Earliness and Tardiness Penalties

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Abstract: In this paper, we propose an innovative hybrid integrated approach between simulated annealing (SA) and control theoretic based distributed arrival time control (DATC), named SA-DATC. The two approaches have been combined to achieve the objective of Just-in-Time (JIT) scheduling in an open-shop system. This approach makes the two algorithms work together aimed with combining the main advantages of each of them, to obtain a reactive control strategy. The SA algorithm plays a role as the machine-route explorer, while the DATC algorithm is inserted into the SA loop, allowing searching for the best arrival times of jobs to satisfy the JIT objective wanted. The performance of this new hybrid SA-DATC approach is evaluated with quadratic linear program solutions to test its relative performance in a static environment. Computational results show that the algorithm performs well on the most of the test problems generated randomly in this paper with an interesting computational time, proving that our approach is favorable for an open-shop scheduling problem.

Keywords: Open shop scheduling, Just-in-Time (JIT), arrival time control, control theory, Distributed Arrival-Time Control (DATC).

1. INTRODUCTION

The paper deals with a scheduling problem of an open-shop system, based on the fixed deadlines for the job in a just-in-time (JIT) production policy. The different problems encountered in scheduling depend mainly on the machines and the sequence of operations (Pinedo (2008)). Among these problems, we are interested in this paper to the open shop scheduling problem with earliness/tardiness measure. An open shop scheduling problem (OSSP) is a kind of shop scheduling such that no technological route is imposed on the jobs. Open shop scheduling problems appear in several industrial situations like automobile repair, semiconductor manufacturing, teacher-class assignments and satellite communications and so on (Liu (2009)).

Scheduling models with both earliness and tardiness(E/T) penalties has been attracting intensive research interest. This type of problem became important with the advent of the Just-in-time (JIT) concept, where early or tardy deliveries are highly discouraged. This concept based on reducing inventory costs and satisfying customer demands, plays an increasingly important role and becomes a relevant criterion for assessing the quality of a production performance (Cho and Lazaro (2010)). It has been known that the multiple machines, multiple job E/T problems are NP-hard. Thus, a large scale problem requires a heuristic procedure for its solution methodology (Heady and Zhu (1998)). The first works date back to the late 70*s* and early 80*s* as shown in the literature survey done by Baker and Sudder (Baker and Scudder (1990)). There are several published papers in literature dealing with scheduling problems with E/T measure. Most of them focus on single and parallel machine problems under different types of restrictive assumptions. Regarding open shop scheduling problem most of published papers are focused on OSS with such regular measures as Makespan and mean flow time (Andresen et al. (2008)), (Liaw (2005)). There are only a few papers studying OSS with total tardiness minimization, (Liaw (2005)). In the case of problems dealing with OSS with non-regular measures as earliness tardiness minimization there is very little paper that deals with this problem, the author in (Heady and Zhu (1998)) developed a new heuristic (idle time rule) for non-preemptive open shop scheduling with minimizing total earliness and tardiness penalties as objective. The problem of minimizing total earliness/tardiness penalty in an open shop scheduling environment with non-identical parallel machines was studied by Doulabi in (Doulabi

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(2010)), another interesting work dealing with JIT OSSP to minimize the sum of the weighted E/T penalties was studied by (Doulabi et al. (2012)).

Based on the above reasons, open chop scheduling with earliness and tardiness cost minimization becomes an interesting problem since it matches the real problems encountered in industry, and the literature on this problem is scarce. The application of control theory techniques for scheduling and dynamic controlling manufacturing systems has been widely recognized in different types of production facilities (Cho and Lazaro (2010)). However its application in scheduling domains presents difficulties due to the strongly nonlinear characteristics inherent of the model, which require changing the dynamics of the system to differential inclusions (Prabhu and Duffie (1995)). The methods were initially used to control the ability of systems and the flows of products using feedback controller, and then recently for distributed decision making in Heterarchical systems (Duffie et al. (2002)). Among these techniques we find the Distributed Arrival-Time Control (DATC) technique which is a highly distributed feedback control that uses feedback from simulations to iteratively refine and improve decisions. It has been studied for a variety of applications include production scheduling, maintenance scheduling, transportation routing, inventory control, supply chain management, etc. It was proposed for the first time as a scheduling methodology for part-driven systems using minimal global information for controlling dynamic environments. Most of the work on this approach deals with single machine system (Cho and Lazaro (2010), Lee and Prabhu (2015), Cho and Prabhu (2002a)). After, it was extended to several machines like the job-shop (Duffie and Kaltjob (1998), Shaikh et al. (2003)) and job shop (Zambrano et al. (2014)).

As far as we reviewed, there is far less papers dealing with the earliness tardiness open shop scheduling problem. Hence, this paper studies open shop scheduling problem under minimization of earliness and tardiness penalties. The paper proposes an innovative hybrid integrated approach between DATC and SA. This hybridization aimed at combining the main advantages of each algorithm, to obtain a reactive control strategy, and make the two algorithms work together. The remaining section of this paper is organized as follows. The second section introduces the characteristics of the Problem studied (OSSP), In the third section we present the proposed hybrid SA-DATC approach. The last section is devoted to experiments performed in order to test and validate the effectiveness of the SA-DATC approach. Finally, we conclude our study and suggest an area for future research.

2. ABOUT THE OPEN-SHOP SCHEDULING PROBLEM - OSSP

2.1 OSSP with a quadratic JIT objective function

An open shop scheduling problem (OSSP) consists of a set of n jobs that should be processed on a set of m machines. An operation $O(i, j)$ refers to the processing of jobs J_j on machine M_i . The processing time of operation $O(i, j)$ is denoted by $P(i, j)$. In an open shop, there are no restrictions on the routing of every job through the machines; the decision maker is allowed to determine a route for each job. Each machine can process at most one job at a time, and each job can be processed on at most one machine at a time. This gives much flexibility in scheduling, but also makes it difficult to develop rules that give an optimum sequence for every problem. Furthermore, preemption is not allowed, that is, the processing of a job on a machine cannot be interrupted. For the JIT objective function, we consider the quadratic relationship between the earliness and tardiness penalties, denoted as the due date mean-square deviation (MSD):

$$MSD = \frac{1}{n}\sum_{j=1}^{n}(E_j^2 + T_j^2) = \frac{1}{n}\sum_{j=1}^{n}(d_j - c_j)^2 \qquad (1)$$

Where E_j is the earliness of job j (a job j is early if $E_j > 0$, $E_j = max\{d_j - c_j, 0\}\forall j \in J)$; T_j is the tardiness of job j (a job j is late if $T_j > 0$, $T_j = max\{c_j - d_j, 0\}\forall j \in J)$; c_j is the completion time of the last operation of job j, and d_j is the job due date.

2.2 DATC and SA for solving the OSSP with JIT Scheduling

For the design of our hybrid approach we consider a two-phase algorithm, in the first phase simulated annealing is used to search for the sequence of jobs, and in the second phase DATC algorithm is used to determine optimal start time of jobs on machines for the input job sequence. In another way, it can be said that the suggested hybridization makes it possible to combine the machine-routing solution-space exploration realized by the simulated annealing and the calculation of release times of the jobs executed by the DATC.

DATC and JIT Scheduling Problem - The proposed control system called Distributed Arrival Time Control (DATC) was proposed by (Prabhu and Duffie (1995)) as scheduling methodology for any part-driven system, where an integral controller is used to determine the arrival times of jobs. The principal of this approach is to associate to each job a controller that adjusts iteratively and autonomously its arrival time behind the feedback of its completion time, in such a way that jobs are completed as possible at its due dates, and the objective is closely or completely achieved fig (1). In discrete flow manufacturing systems, arrival time is the time in which the product enter into shop floor, reaches a queue of machine or start a specific production process. This control system is not only highly distributed due to its use of local variables and local control laws, but also decisions control are taken in real-time enabling to react to events that occur randomly in the manufacturing systems (Cho and Prabhu (2002a)). The release of a product in the workshop affects its own queuing times, its processing times and completion times, as well as those of other products with which it interacts. The mathematical expression for the DATC controller is expressed in the equation 2:

$$a_j(t) = k_j \int_0^t (d_j - c_j(\tau)).d\tau + a_j(0) \qquad (2)$$

Where a_j, c_j and d_j denote respectively the arrival time, completion time, and due date of a job j, and k_j denotes its

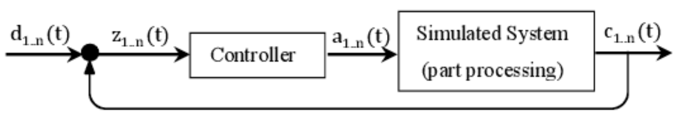

Fig. 1. Closed loop multi-variable distributed control structure of DATC

control system gain. $a_j(0)$ is an arbitrary initial condition, and τ is the integration variable, which can take values from 0 to t. When there is no queuing and capacity is sufficient for the requested jobs, due-date deviations converge to zero. When capacity is not sufficient, the controller adjusts the arrival times, penalizing equally earliness and tardiness. The completion times are calculated by the simulation module according to a first-come-first-served (FCFS) dispatching policy, which is applied to each iteration based on current arrival times. The completion time for each job j is calculated as in equation 3:

$$c_j(t) = a_j(t) + \sum_{i \in M} p_{ij} + \sum_{i \in M} q_{ij} \quad (3)$$

In this study, we consider the static case; the machine failure, transportation time, and setup time are zero, and jobs completion time depends only on the sum of processing times of the different processing steps of this job, and a sum of queuing time at each machines of jobs root q_{ij}. In most works on the DATC approach, the criteria describing the mean square deviation (MSD) from due dates were always used as in equation 1, penalizing severely large deviations around them. The resulting multivariate control system in R^n is illustrated in Figure 1.

Simulated Annealing (SA) - Simulated Annealing is an enhanced version of local optimization. The SA algorithm is inspired by a metallurgical process called annealing, which refers to the process when physical substances are raised to a high energy level and then gradually cooled until some solid state is reached. The goal of this process is to reach the lowest energy state. In this process physical substances usually move from higher energy states to lower ones if the cooling process is sufficiently slow. However, there is some probability at each stage of the cooling process that a transition to a higher energy state will occur, but this probability of moving to higher energy state decreases in this process (Zhang (2013), Andresen et al. (2008)). The simulated annealing accepts a worse solution with a certain probability. This one depends on the decreasing temperature so a local optimum is avoided. It starts from an initial basic solution (S) and randomly generates a neighbor solution (S^*) from its neighborhood. The difference in the objective function values $\delta = f(S^*) - f(S)$ is calculated. If $\delta < 0$ the objective function value of the new solution S^* is better than that of the current solution, S is replaced with S^*. Otherwise, the generated neighbor solution S^* may also be accepted with a probability $e^{(-\delta/T)}$, where T is a control parameter called the temperature. This parameter is gradually decreased by a constant cooling rate in each iteration. $T = \alpha T$.

3. PROPOSED HYBRID SA-DATC APPROACH

The purpose of the hybridization of SA-DATC concept is to maintain a range of valid solutions, and to operate the two algorithms together. With this proposed integration, the advantage is twofold: firstly, the RS benefits from the DATC because of the integration of a continuous variable, the release time of job. Secondly, the DATC benefits from machine routing filtering process executed by SA. In what follows we present the 2 phases.

3.1 Phase I- Job sequence search using simulated annealing

The simulated annealing method used in this study was designed to find the near optimal sequence of jobs. The first two most relevant steps for the application of the SA algorithm for scheduling are the representation of the initial solution structure and generation of its neighbors. We describing the tow steps in the two next subsections

Solution Representation - Inspired from (Seyed and Hossein (2012)), the initial solution is generated as a matrix with n rows and m columns containing random values between 0 and 1. Lines represent jobs and columns represent machines. An example of this matrix for a problem with 3 machines and 3 jobs is shown in Fig 2a. The determination of machine sequence which processes the job j is done by sorting in ascending order the entries of the line j, as shown on Fig 2b for the job 2.

	M1	M2	M3
J1	0.56	0.23	0.85
J2	0.71	0.11	0.28
J3	0.14	0.65	0.37

(a)

	M1	M2	M3
J2	0.71	0.11	0.28

Sorting

	M2	M3	M1
J2	0.11	0.28	0.71

(b)

Fig. 2. Solution Presentation of DATC

Neighbor generation operators - As explained before, in this section, 3 neighbor generator operators are used. (i) The first one consists on interchanging the position of two random rows in the current solution. It means that machine sequences of two jobs are changed simultaneously ; (ii) Like the first one, the second one consists on interchanging the position of two random columns in the current solution. It means that job sequences of two machines are changed ; (iii) The third operator, consist on interchanging tows random operation selected and replaced together from the matrix solution. The choice of an operator i which will be selected to generate the neighbor, is done at each iteration according to a random probability mechanism $p_i, (i = \{1, 2, 3\}$ and $p_1 + p_2 + p_3 = 1$).

3.2 Phase II- Setting start time of jobs using a DATC

In this section, we develop the second phase corresponding to the setting start time of jobs on machines using a DATC. At first, the SA generates an initial random solution matrix using the above-mentioned neighbor generator operators, thus a machine path for each job will be determined, and then the algorithm of the DATC inserted into the SA loop will be unrolled until the MSD reaches its stable state. At this time the start time of each job ST_j are obtained and the objective function can be evaluated. Based on the value of the neighboring solution $(f(S^*)), \delta = f(s^*) - f(s)$ is calculated and the decision on the transition to the next solution could be made. The algorithm stops when the value of the best found objective function is equal to a lower bound or the temperature is lower than a predetermined parameter called the cooling temperature. In addition, a time limit is another stop criterion for the algorithm described on the Fig 3.

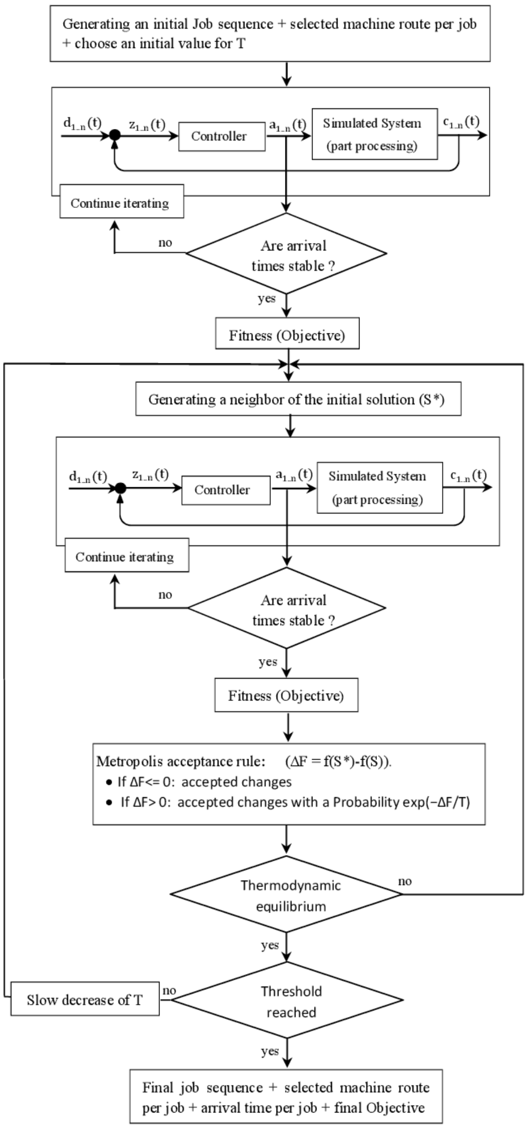

Fig. 3. Algorithm of the proposed approach

4. COMPUTATIONAL EXPERIMENTS

In this section we describe our experiments to evaluate the performance of the proposed hybrid approach SA-DATC. As we found no papers on open-shop scheduling problem with the same objective function as this paper. Therefore, the evaluation of SA-DATC is somewhat difficult. In order to overcome this difficulty, we have randomly generated some tests problems ranging from a small-sized problems to relatively large-sized ones considering the following combinations for the number of n jobs and m machines: $(3 \times 2)(3 \times 3)(4 \times 3)(5 \times 3)(10 \times 5)(20 \times 5)$. We considered 5 instances for each problem which is characterized by n number of jobs, m number of machines, P_{ij} the range of processing times for each operation of each job and d_j due date for each job. The integer processing times for all operations are generated independently from a uniform distribution on the interval $[1, 15]$. Due date for every job j is considered to be $d_j = \beta * \sum_i P_{ij}$ in which $\beta > 1$ is a constant parameter. For $\beta = 1.1, 1.2$, and 1.3, different due dates are generated.

The parameters of the DATC design are integral gain are synthesized according to the processing time of each job $k_j = \sum_i(P_{ij})/max \sum_i(P_{ij})$ and duration of numerical simulation has been set to 500 iterations. For the SA experiments also we have set initial temperature, cooling rate, inner and outer loop bounds, P1, P2, P3 to 10, 0.9, 50, 0.3, 0.3, 0.4 respectively. no-improvement and time-limit parameters are also fixed to 40, and 300 s.

The QLP used to compare the performance of the proposed hybridized method was inspired from the mixed integer linear formulation of E/T open shop scheduling based on sequence-based variables proposed by (Doulabi (2010)). In order to obtain a QLP for the open shop scheduling problem considered in this paper, the objective function was changed from minimizing summation of weighted E/T penalties to minimizing the mean squared deviation of E/T penalties. Due to the problem combinatorial complexity For larges problems instances, the QLP reports heuristic solutions when CPLEX is stopped after a fixed amount of time (1h). We specify that the development of SA-DATC algorithm was accomplished in Matlab while QLP Model was solved using IBM ILOG Cplex 12.2, on a PC Intel (R) Core (TM) i3-2100, 3.10 GHz, 6 GB of RAM. For each problem the solution gap (deviation from the optimal solution) is defined by

$$Gap = \frac{MSD_{SA-DATC} - MSD_{QLP}}{MSD_{QLP}} * 100\% \qquad (4)$$

Where $MSD_{SA-DATC}$ is the solution obtained bey $SA-DATC$ approach and MSD_{QLP} is the solution obtained by the QLP model. Due to the stochastic nature of $SA-DATC$ method, the reported $MSD_{SA-DATC}$ is the best of 5 independent trials for each case. The gap between $SA-DATC$ method and the QLP is calculated as in Equation (4), but in some cases where $MSD_{QLP} = 0$, the $Gap = MSD_{SA-DATC}$ because of the division by zero.

The detailed results of SA-DATC approach are presented in Table 1; the results are also compared to those obtained by the QLP model. The analysis of the results will be done on the quality of the solutions obtained by our approach and the computational time required. We can distinguish two groups of test problem, In the first group with small sized instances we have problem test $(3 \times 2)(3 \times 3)(4 \times 3)$ and (5×3) , in this group the QLP model can find the optimal solution in a reasonable amount of time less than one hour. It can be seen from Table 1 that, SA-DATC yields excellent results, in the first problem test (3×2) we remark in many cases, an optimum solution is found, and in others the distance from the optimum is quite small for all β, with a very little computing times despite that they are a little lower than those of QLP model. same analysis was noticed for the second problems test with n=m=3 , in this problem test the most of the QLP results are equal to zero then in this special case the Gap equal to the difference between SA-DATC and QLP. By a little increasing of the combinatorial complexity towards the 2 other problem test (4×3) and (5×3) our approach always obtains good near optimal results for all β. Also we can Remarque a significant increase in computational time of the QLP model which exploded especially in the 4^{th} test problem (5×3), which can exceed 1000s in computational time, however does not exceed 5s for SA-DATC approach. The results show that the solutions Gap increase slightly when the number of jobs increase. The second group of large instances designed by the combination $(10 \times 5)(20 \times 5)$, we remark that the solution obtained by the heuristic SA-DATC is so much better than those obtained by the QLP model. Considering computational time the proposed hybrid approach is faster than the QLP model, it can considered as a promising approach for solving the just in time open shop scheduling problem.

5. CONCLUSION

Open shop scheduling problem with minimizing the mean squared deviation of completion time about due dates has been considered in this paper. The use of control theory for JIT scheduling problems was approved by the application of a (DATC) approach. The application of this method requires the definition in advance of the machine-routing of the different jobs; this is why in the case of an open shop system we thought to hybridize it with another heuristic that will explore the jobs machine-routing. For this reason a new hybrid approach called SA-DATC has been proposed, which is an integrated combination of two heuristics, the first is simulated annealing, which is simple, fast and has the possibility of escaping the local minima, and whose mission is to look for the machine-routing. The second one is the DATC, whose role is to look for the arrival time of jobs, so that their completion times are equal to their predetermined due dates. By combining the properties of SA and DATC and according to the results obtained, the hybrid algorithm SA-DATC proposed is remarkably efficient for solving the real time open shop scheduling problem in a JIT manufacturing environment.

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Table 1. Results for small-sized problems.

n	m	inst	β=1.1					β=1.2					β=1.3				
			QLP		SA-DATC		Gap(%)	QLP		SA-DATC		Gap(%)	QLP		SA-DATC		Gap(%)
			MSD	Time(s)	Avg. MSD	Time(s)		MSD	Time(s)	Avg. MSD	Time(s)		MSD	Time(s)	Avg. MSD	T(s)	
3	2	1	36,76	0,48	36,76	1,35	**0,00**	14,89	0,53	14,89	1,30	**0,00**	3,08	0,49	3,08	1,30	**0,00**
3	2	2	26,90	0,52	26,90	1,23	**0,00**	15,93	0,92	15,93	1,19	**0,00**	10,1	0,82	10,10	1,35	**0,00**
3	2	3	35,38	0,78	35,38	1,20	**0,00**	17,31	0,80	18,00	1,31	**3,99**	6,12	0,54	6,12	1,22	**0,00**
3	2	4	31,46	0,46	31,46	1,27	**0,00**	18,37	0,50	18,37	1,21	**0,00**	8,34	0,52	8,34	1,25	**0,00**
3	2	5	17,18	0,46	17,18	1,21	**0,00**	7,21	0,82	7,27	1,20	**0,83**	2,94	0,84	3,45	1,20	**17,35**
3	3	1	1,20	2,09	1,53	2,15	**27,50**	0,00	0,76	0,39	1,81	**39,00**	0,00	0,32	0,27	1,87	**27,00**
3	3	2	1,71	1,52	1,80	1,91	**5,26**	0,00	0,99	0,08	2,29	**8,00**	0,00	0,79	0,08	2,10	**8,00**
3	3	3	0,25	0,68	0,25	2,20	**0,00**	0,00	0,45	0,29	2,07	**29,00**	0,00	0,49	0,21	1,86	**21,00**
3	3	4	1,71	0,78	1,74	2,36	**1,75**	0,00	0,65	0,17	2,25	**17,00**	0,00	0,33	0,05	2,16	**5,00**
3	3	5	0,74	0,68	0,82	2,34	**10,81**	0,00	1,16	0,27	2,07	**27,00**	0,00	0,75	0,14	2,09	**14,00**
4	3	1	52,93	8,37	52,93	3,61	**0,00**	26,35	7,81	26,76	2,66	**1,56**	12,33	29,25	13,00	2,46	**5,43**
4	3	2	37,31	14,29	42,86	4,07	**14,88**	19,36	18,72	20,57	3,39	**6,25**	9,61	8,46	11,50	2,90	**19,67**
4	3	3	35,51	22,99	38,21	2,83	**7,60**	16,70	9,70	18,10	2,98	**8,38**	4,25	6,70	4,56	3,44	**7,29**
4	3	4	52,01	32,41	52,01	3,17	**0,00**	22,18	38,48	27,74	3,00	**25,07**	7,33	10,06	8,54	2,39	**16,51**
4	3	5	33,39	18,48	33,39	3,04	**0,00**	12,76	14,11	12,76	3,53	**0,00**	3,31	17,92	3,31	2,31	**0,00**
5	3	1	70,9	591,47	82,54	4,46	**16,42**	38,96	901,01	52,56	4,14	**34,91**	16,18	592,70	20,80	4,62	**28,55**
5	3	2	98,85	1649,73	115,25	3,71	**16,59**	56,92	453,28	65,88	3,63	**15,74**	29,41	644,36	32,65	3,51	**11,02**
5	3	3	151,42	1575,72	181,14	3,58	**19,63**	100,54	1601,46	101,58	4,28	**1,03**	57,42	2299,75	62,86	4,21	**9,47**
5	3	4	230,34	48,95	254,57	4,37	**10,52**	168,38	26,59	183,52	4,10	**8,99**	117,63	18,70	124,49	3,99	**5,83**
5	3	5	58,75	485,97	67,23	3,83	**14,43**	30,45	252,9	34,70	4,35	**13,96**	10,78	1207,35	12,39	4,13	**14,94**
10	5	1	2598,10	3600	1571	35,32	**-39,53**	2298,58	3600	1130	38,22	**-50,84**	1898,09	3600	966,81	37,30	**-49,06**
10	5	2	3231,64	3600	1400	37,97	**-56,68**	2546,47	3600	1080	39,66	**-57,59**	2013,20	3600	885,93	48,84	**-55,99**
10	5	3	3802,04	3600	1700	41,09	**-55,29**	3351,18	3600	1460	41,66	**-56,43**	4279,48	3600	967	36,88	**-77,40**
10	5	4	2380,19	3600	1170	34,56	**-50,84**	2432,88	3600	979	45,23	**-59,76**	1990,66	3600	623,24	25,18	**-68,69**
10	5	5	4341,35	3600	1390	38,96	**-67,98**	3359,72	3600	1120	38,17	**-66,66**	2859,59	3600	950,11	36,35	**-66,77**
20	5	1	15394,69	3600	13300	115,78	**-13,61**	14429,25	3600	12000	169,59	**-16,84**	13507,77	3600	10900	163,91	**-19,31**
20	5	2	16173,34	3600	14400	146,13	**-10,96**	15135,33	3600	13500	179,8	**-10,80**	14145,63	3600	12800	123,23	**-9,51**
20	5	3	12469,96	3600	12400	131,3	**-0,56**	11567,27	3600	12000	146,89	**3,74**	10709,26	3600	11900	171,02	**11,12**
20	5	4	13479,34	3600	10700	186,44	**-20,62**	12675,92	3600	9510	188,98	**-24,98**	11907,09	3600	9000	170,62	**-24,41**
20	5	5	14562,74	3600	10400	133,92	**-28,58**	13911,08	3600	10400	134,42	**-25,24**	12956,17	3600	8630	160,05	**-33,39**