

Dispatching Rules for Production Scheduling: a Hyper-heuristic Landscape Analysis

Gabriela Ochoa, José Antonio Vázquez-Rodríguez, Sanja Petrovic and Edmund Burke

Abstract—Hyper-heuristics or “heuristics to chose heuristics” are an emergent search methodology that seeks to automate the process of selecting or combining simpler heuristics in order to solve hard computational search problems. The distinguishing feature of hyper-heuristics, as compared to other heuristic search algorithms, is that they operate on a search space of heuristics rather than directly on the search space of solutions to the underlying problem. Therefore, a detailed understanding of the properties of these heuristic search spaces is of utmost importance for understanding the behaviour and improving the design of hyper-heuristic methods. Heuristics search spaces can be studied using the metaphor of fitness landscapes. This paper formalises the notion of hyper-heuristic landscapes and performs a landscape analysis of the heuristic search space induced by a dispatching-rule-based hyper-heuristic for production scheduling. The studied hyper-heuristic spaces are found to be “easy” to search. They also exhibit some special features such as positional bias and neutrality. It is argued that search methods that exploit these features may enhance the performance of hyper-heuristics.

I. INTRODUCTION

Despite the success of evolutionary algorithms and other heuristic search methods in solving real-world computational search problems, there are still some difficulties for easily applying them to newly encountered problems, or even new instances of known problems. These difficulties arise mainly from the significant range of parameter or algorithm choices involved when using this type of approaches, and the lack of guidance as to how to proceed for selecting them. Another drawback of these techniques is that state-of-the-art approaches for real-world problems tend to represent bespoke problem-specific methods which are expensive to develop and maintain. Hyper-heuristics or “heuristics to chose heuristics”[3] are an emergent search methodology that seeks to automate the process of selecting or combining simpler heuristics in order to solve hard computational search problems. The main motivation behind hyper-heuristics is to raise the level of generality in which search methodologies can operate. A hyper-heuristic approach consists of a high-level general strategy that coordinates the efforts of a set of low-level (usually problem specific) heuristics to solve the underlying problem. The distinguishing feature of hyper-heuristics, as compared to other heuristic search algorithms, is that they operate on a search space of heuristics rather than directly on the search space of solutions to the underlying

problem. In consequence, a detailed understanding of the properties of these heuristics search spaces is of utmost importance for understanding the behaviour and improving the design of hyper-heuristic methods. Heuristic search spaces can be studied using the metaphor of fitness landscapes, in which the search space is regarded as a spatial structure where each point (solution) has a height (objective function value) forming a landscape surface. Both local and global features of search landscapes can be estimated by statistical methods (see [18] for an introduction to landscape analysis).

In the domain of Job-Shop Scheduling, Fisher and Thompson [9], [10] hypothesised that combining scheduling rules (also known as priority or dispatching rules) would be superior than any of the rules taken separately. This pioneering work, well ahead its time, proposed a method of combining scheduling rules using “probabilistic learning”. Notice that in the early 60s, meta-heuristic and local search techniques were still not mature. However, the proposed learning approach resembles a stochastic local search algorithm (indeed a estimation of distribution algorithm) operating in the space of scheduling rule sequences. The main conclusions from this study are the following: “(1) an unbiased random combination of scheduling rules is better than any of them taken separately; (2) learning is possible” [10]. The ideas by Fisher and Thompson [9], [10] were independently rediscovered and enhanced, several times, 30 years later [7], [8], [20], [21], when modern meta-heuristics were already widely known and used. Therefore, the authors had the appropriate conceptual and algorithmic tools (also the computer power) to propose and conduct search within a heuristic search space. More recent studies using dispatching rules as low-level heuristics in hyper-heuristic approaches are those described in [22], [23].

This paper conducts a landscape analysis of the heuristic search space induced by the dispatching-rule-based hyper-heuristic for production scheduling presented in [22], [23]. The underlying problem studied is the hybrid flowshop scheduling problem. Dispatching rules are among the most frequently applied heuristic in production scheduling, due to their ease of implementation and low time complexity. Whenever a machine is available, a dispatching rule inspects the waiting jobs and selects the job with the highest priority to be processed next. Dispatching rules differ from each other in the way they calculate priorities. A candidate solution in the studied heuristic space is, therefore, given by a sequence (list) of dispatching rules. Each rule in this list is successively used to select one operation (or group of operations) to be assigned next to its required machine.

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The paper is structured as follows. Section II describes the underlying problem domain and the hyper-heuristic approach under study. Thereafter, section III describes the notion of fitness landscapes and the metrics employed in our analysis; it also presents a formal definition of hyper-heuristics landscapes. Section IV describes our methodology, whilst section V reports our results regarding performance and landscape analysis. Finally, section VI, summarises and discusses our main findings.

II. A HYPER-HEURISTIC APPROACH TO THE HYBRID FLOW SHOP PROBLEM

The hybrid flow shop scheduling problem (HFS) consists of assigning n jobs into m processing stages; all jobs are processed in the same order: stage 1, stage 2, \dots , until stage m . At least one of the stages has two or more identical machines working in parallel. No job can be processed on more than one machine at a time, and no machine can process more than one job at a time. Several objective functions have been proposed for the HFS. Let c_j and d_j be the completion time of job j , i.e. the time when it exists the shop, and its due date, respectively. We considered two objective functions for measuring the quality of the schedules: (1) the makespan denoted C_{max} and defined as $C_{max} = \max_j(c_j)$ and (2) the total weighted tardiness, denoted $sumWT$ and defined as $sumWT = \sum_{j=1}^n w_j \cdot \max\{0, c_j - d_j\}$, where w_j is a weight associated with job j . The interested reader is referred to [24] for a more detailed description of HFS formulation and objective functions, and a review of approaches developed for the problem.

The HFS is very common in real world manufacturing. It is encountered in the electronics industry, ceramic tiles manufacturing, cardboard box manufacturing and many other industries. HFS scheduling is an NP-Hard problem, even when there are just two processing stages with one of them having a single machine, and one having parallel machines [12]. The relevance and complexity of the HFS problem have motivated the investigation of a variety of methods including: exact methods [5], [25], heuristics [19], [6], meta-heuristics [11], [1], and more recently hyper-heuristics [22], [23]

Since there are n jobs to be processed in m stages, the number of decisions to be made is $N = n \times m$. Therefore, decisions 1 to n correspond to the scheduling of operations in the first stage of the shop, from n to $2n$ to jobs in the second stage of the shop and so on. Let us consider the task of deciding the order in which n jobs have to be scheduled on a machine for a given stage. Fulfilling this task requires deciding which job is to be processed 1st, which job is to be processed 2nd and so on. Let d_1 be the first of these decisions, d_2 the 2nd, and so on. The task requires, then, $n - 1$ decisions (no decision is required when there is one job left). Let D be the set of all decisions defining a problem and $N = |D|$.

Definition 1: $D = \{d_1, \dots, d_N\}$ is the set of decisions defining a problem, where d_i is the i^{th} decision to be made.

Let us give an illustrative example: suppose 7 jobs are to be scheduled, i.e. $n = 7$, and for simplicity let us assume a

single stage ($m = 1$). Thus, $D = \{d_1, \dots, d_6\}$. Let us denote by p_j the processing time of job j . The processing times of the jobs are $p = \{10, 20, 30, 40, 50, 60, 70\}$. Let H be the repository of low level heuristics, i.e. the set of heuristics which are available to make the decisions in D . Suppose H contains two elements; h_1 : *assign next the not-yet scheduled job with the shortest processing time*; and h_2 : *assign next the not-yet scheduled job with the longest processing time*. A feasible solution to the given 7 jobs scheduling problem can be obtained as follows.

Step 1: assign a low level heuristic from H to each of the decisions in D . Let $a_i \in H$ be the heuristic assigned to d_i .

Step 2: call successively a_1, a_2, \dots, a_6 to select the 1st, 2nd, \dots , 6th job to be processed.

Step 3: assign last the remaining operation and calculate the starting and completion times of jobs.

In this way a search mechanism, such as a genetic algorithm (GA), may be used to find a sequence of heuristics in the form $\mathcal{A} = [a_1, a_2, \dots, a_6]$ which is translated into a solution as explained above. Suppose that the following assignment of heuristics is generated by the GA, $\mathcal{A}' = [h_1, h_1, h_1, h_2, h_2, h_2]$. Using the described procedure, this translates into the sequence of jobs 1, 2, 3, 7, 6, 5, 4. A schedule is obtained by calculating the starting and completion time of each job. The task of the GA algorithm or any other heuristic search mechanism, then, would be to decide which element of H to assign to each a_i . In consequence, the size of the heuristic search space (for each stage) is in this case 2^6 , as there are two possible heuristics for each of the 6 assignments.

As discussed in [23] the scheduling decisions can be grouped into *decision blocks*. In the above example, an assignment of heuristics with the form $\hat{\mathcal{A}} = [\hat{a}_1, \hat{a}_2, \hat{a}_3]$ may also represent a feasible solution if it is translated into a schedule as follows.

Step 1: assign \hat{a}_1 to d_1 and d_2 ; assign \hat{a}_2 to d_3 and d_4 ; assign \hat{a}_3 to d_5 and d_6 .

Steps 2 and 3: as above.

In this way, $\hat{\mathcal{A}}' = [h_1, h_2, h_1]$ translates into 1, 2, 7, 6, 3, 4, 5. In this second type of assignment ($\hat{\mathcal{A}}$) the decisions were grouped in 3 blocks, having two operations each (the last block has 3 operations).

Notice that in this case, the size of the search space decreases to 2^3 as we have now only 3 assignments to make. More generally, the size of the heuristic space will be $|H|^{|\hat{\mathcal{A}}|}$, where H denotes the repository of heuristics, and $\hat{\mathcal{A}}$, the sequence of assignments.

III. FITNESS LANDSCAPES

The notion of fitness landscapes [18] was introduced to describe the dynamics of adaptation in nature [26]. Since then, it has become a powerful metaphor in evolutionary theory. The fitness landscape metaphor can be used for search

in general. Given a search problem, the set of possible solutions can be coded using strings of fixed length from some finite alphabet. This encoding generates a representation space, which is a high dimensional space of all possible strings of a given length. There is also a neighborhood relation that defines which points in the representation space are connected. This relation depends on the specific search operator or combination of operators, used to search the space. Finally, there is a fitness function that assigns a fitness value to each possible string or point in the space.

More formally [15], a fitness landscape (S, f, d) of a problem instance of a given combinatorial optimization problem consists of a set of candidate solutions S , a fitness (or objective) function $f : S \mapsto R$, which assigns a real-valued fitness to each solution in S , and a distance metric d that defines the spatial structure of the landscape. This distance is related to the neighborhood relation described above.

A. Fitness distance correlation analysis

The most commonly used measure to estimate the global structure of fitness landscapes is the *fitness distance correlation (FDC)* coefficient, proposed by Jones and Forrest [13]. It is used as a measure for problem difficulty in genetic algorithms. Given a set of points x_1, x_2, \dots, x_m and if fitness values, the FDC coefficient ϱ is defined as:

$$\varrho(f, d_{opt}) = \frac{Cov(f, d_{opt})}{\sigma(f)\sigma(d_{opt})} \quad (1)$$

where $Cov(., .)$ denotes the covariance of two random variables and $\sigma(.)$ the standard deviation. The *FDC* determines how closely related are the fitness of a set of points and their distances to the nearest optimum in the search space (denoted by d_{opt}). If fitness increases when the distance to the optimum becomes smaller, then the search is expected to be easy, since the optimum can gradually be approached via fitter individuals. A value of $\varrho = -1.0$ ($\varrho = 1.0$) for maximisation (minimisation) problems indicates a perfect correlation between fitness and distance to the optimum, and thus predicts an easy search. On the other hand, a value of $\varrho = 1.0$ ($\varrho = -1.0$), means that with increasing fitness the distance to the optimum increases too, which indicates a deceptive and difficult problem. As suggested in [13], a value of $fdc \leq -0.5$ ($fdc \geq 0.5$) for maximisation (minimisation) problems indicates an easy problem.

Often, a fitness distance plot is made to gain insight into the structure of the landscape, in addition to (or instead of) calculating the correlation coefficient [15]. This is done by plotting the fitness of points in the search space against their distance to an optimum or best-known solution. This type of analysis, often called *fitness distance analysis*, can be used to investigate not only the correlation between arbitrary points in the search space, but also the distribution of local optima within the search space. An interesting property of fitness landscapes, which has been observed in many different studies [2], [14], [15], [17], is that on average, local optima are very much closer to the optimum than

are randomly chosen points, and closer to each other than random points would be. In other words, the local optima are not randomly distributed, rather they tend to be clustered in a “central massif” (or “big valley” if we are minimising). This global structure has been observed in the abstract *NK* family of landscapes [14], and in many combinatorial optimisation problems, such as the traveling salesman problem [2], graph bipartitioning [15], and flowshop scheduling [17].

B. Hyper-heuristic Landscapes

Our hyper-heuristic approach (described in section II), deals with two search spaces: (1) the search space of heuristics (HS), and (2) the search space of solutions to the problem at hand (PS). However, we have a single landscape, as the objective function value of a point in the heuristic search space, can only be known after calculating the objective value of the corresponding search point in the solution space. Figure 1 illustrates the two search spaces discussed and the two mappings involved, namely, g from a heuristic list to its corresponding problem solution, and f from the solution to the objective value. More formally, the objective function of a sequence of heuristics \hat{A} in the heuristic space HS is given by the composition of g and f , namely, $f(g(\hat{A})) : HS \mapsto R$. The hyper-heuristic landscape is, therefore, defined as the triplet $(HS, f(g), V)$, where the first two components are defined as above, and V represents the neighbourhood produced by the minimal possible move operator on the heuristic search space (referred to as $1 - move$). That is, the operator that substitutes one heuristic in the sequence by another (randomly selected) heuristic from the repository of low-level heuristics.

IV. EXPERIMENTAL SETTINGS

Two groups of experiments were conducted, the first group compares the performance attained by different problem representations (search spaces), defined by grouping decisions in different block sizes. A direct encoding of the problem based on permutations (i.e. a permutation search space), is a also explored.

Four instances of the hybrid flowshop problem were randomly generated with different numbers of jobs, $n \in \{50, 100\}$, and stages, $m \in \{5, 20\}$. The processing times were generated randomly using a discrete uniform distribution in the $[10, 100]$ interval. Note that the processing time of jobs in different stages may differ. The number of machines per stage were either 4 or 5, both with equal probability.

For each problem instance, several ways of grouping decisions were studied. The representation that considers each decision individually, was always considered. In this representation there are n blocks of size 1 per stage; since there are m stages, there is a total of $n \times m$ decision blocks. Let us consider for example the case of 50 jobs, the distribution of decision blocks in stages is as follows:

$$\underbrace{b_1, \dots, b_{50}}_{\text{stage 1}}, \underbrace{b_{51}, \dots, b_{100}}_{\text{stage 2}}, \dots, \underbrace{b_{50(m-1)+1}, \dots, b_{50m}}_{\text{stage } m}$$

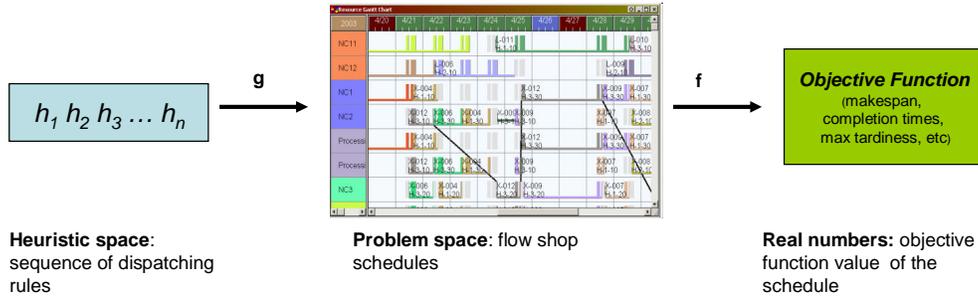


Fig. 1. Hyper-heuristic mapping process from a sequence of heuristics to its fitness value. Two mappings are involved: $g : HS \mapsto PS$, and $f : PS \mapsto R$.

For $n = 50$, decisions were also grouped into 10 and 30 decision blocks per stage. When 10 blocks per stage are considered, each block contains 5 decisions, and when 30 blocks are considered, the first 20 blocks contain 2 decisions each whilst the last 10 one decision each. Similarly, for $n = 100$, blocks of size 25, 50, and 100 were used.

A repository of 13 dispatching-rules were considered as low-level heuristics to be potentially assigned to each decision. These heuristics works as follows: whenever a machine is idle, select the job not yet scheduled and ready for processing (released from the previous stage) that best satisfies a certain criterion and assign it to the idle machine. The following rules were considered: *minimum release time*, *shortest processing time*, *longest processing time*, *less work remaining*, *more work remaining*, *earliest due date*, *latest due date*, *weighed shortest processing time*, *weighted longest processing time*, *lowest weighted work remaining*, *highest weighted work remaining*, *lowest weighted due date* and *highest weighted due date*.

A standard GA with elitism was employed as the high-level strategy searching on the different heuristic spaces, and the permutation space. The crossover operator implemented selects two chromosomes as parents, and sets any gene c_i of the new chromosomes with a probability α from the fittest parent and $1-\alpha$ from the other. The mutation operator selects $(n \times m) \times \beta$ random genes and substitutes them with a different randomly selected dispatching rule. Parameter β ($0 < \beta < 1$) controls the strength of mutation. The GA control parameters that produced the best results after an statistical tuning process [23] were used, namely: a population size of 100, and binary tournament selection with elitism. The algorithm selects the genetic operators independently to produce offspring; crossover with a probability of 0.9, and mutation with 0.1. The α and β parameters described above are set to 0.5 and 0.05, respectively. The stopping condition was set to 10 000 solution evaluations, and for each instance and representation 30 GA runs were conducted.

V. RESULTS

Table I, summarises the average performance obtained after 30 GA runs for each representation and objective function on the four instances studied. The best obtained results for each instance and objective function are highlighted in bold font. Notice that the hyper-heuristic representation clearly outperformed the permutation representation in all cases, and the advantage of the heuristic representation is more noticeable for the *sumWT* objective function. Note also that grouping several decisions into blocks, that is, having shorter hyper-heuristic representations, seems to be favourable when considering a fixed computational effort. This was already observed in [23], where it was also found that considering too many or too few decision blocks per stage yielded comparably poor results. A large number of decision blocks per stage implies a larger search space, whereas very few decision blocks have very limited expression power, this may explain the observed behaviour.

A. Landscape analysis

It is clear from the results discussed above that the hyper-heuristic search spaces offer an advantage when solving HFS problems. With the aim of gaining a better understanding of the structure of such search spaces, this section reports our statistical landscape analysis.

1) *Heuristic space vs. permutation space: distribution of objective values*: First, we compared the distribution of objective values, for both C_{max} and *sumWT*, of a set of 10 000 randomly generated solutions on both the permutation and hyper-heuristic search spaces. The permutation space was sampled by generating random permutations which were decoded as schedules by assigning jobs in their order of appearance into the first machine to become available. The schedules were generated in such a way that there are no idle time windows on any machine that are large enough to process a job without delaying the completion time of any other job. Therefore, only active schedules were generated,

TABLE I

MEAN AND STANDARD DEVIATION OF 30 GA RUNS WITH BOTH OBJECTIVE FUNCTIONS (C_{max} AND $sumWT$), ON THE FOUR STUDIED INSTANCES. THE DIFFERENT HEURISTIC REPRESENTATIONS (NUMBER OF DECISION BLOCKS), AND THE PERMUTATION REPRESENTATION, ARE REPORTED

n	m	representation	Cmax	stDev	sumWT	stDev
50	5	10	941.30	3.74	41341.80	562.78
		30	940.60	3.10	41391.20	745.09
		50	941.00	3.86	41858.90	392.51
		permutation	1042.90	11.60	56107.20	2010.44
	20	10	1755.30	14.45	28481.20	1272.17
		30	1754.00	8.87	28338.40	728.53
		50	1756.50	13.90	28565.50	1174.17
		permutation	2100.80	7.98	65127.70	2305.55
100	5	25	1533.10	3.03	250794.30	3424.25
		50	1523.80	2.86	252856.80	4217.34
		100	1526.10	4.33	256871.20	4814.65
		permutation	1610.20	7.05	303553.80	9260.10
	20	25	2497.20	6.84	195557.50	4076.09
		50	2504.70	11.43	200104.20	3686.10
		100	2508.60	11.70	208216.30	6002.94
		permutation	3072.20	20.98	379926.20	7898.86

which are on average better than most random schedules [16]. The heuristic space was sampled by producing random sequences of dispatching rules, considering the maximum number of decision blocks (i.e. one heuristic per decision). Figures 2 and 3 show the empirical distributions obtained for the two objective functions (C_{max} and $sumWT$), respectively, on the four studied instances. Notice that for both objective functions the solutions represented as sequences of dispatching rules are significantly better than those represented as permutations. This is specially noticeable for the larger instances (i.e. with $m = 20$).

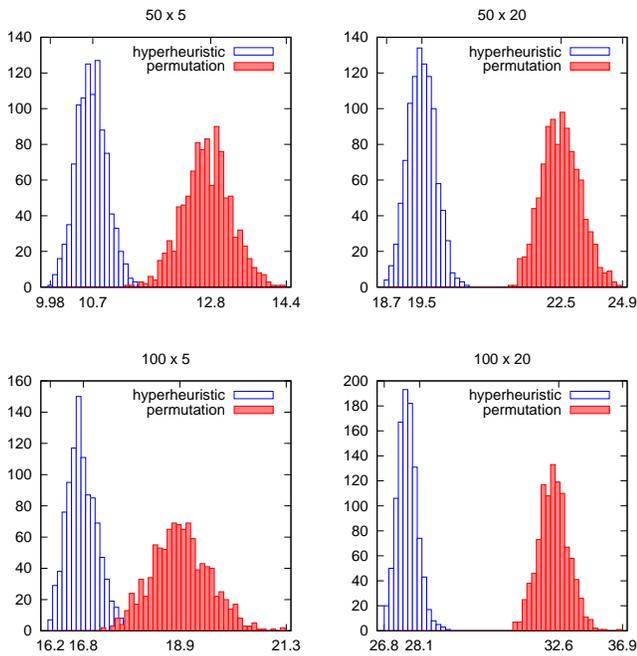


Fig. 2. Distribution of C_{max} values of random solutions of the hyperheuristic and permutation spaces

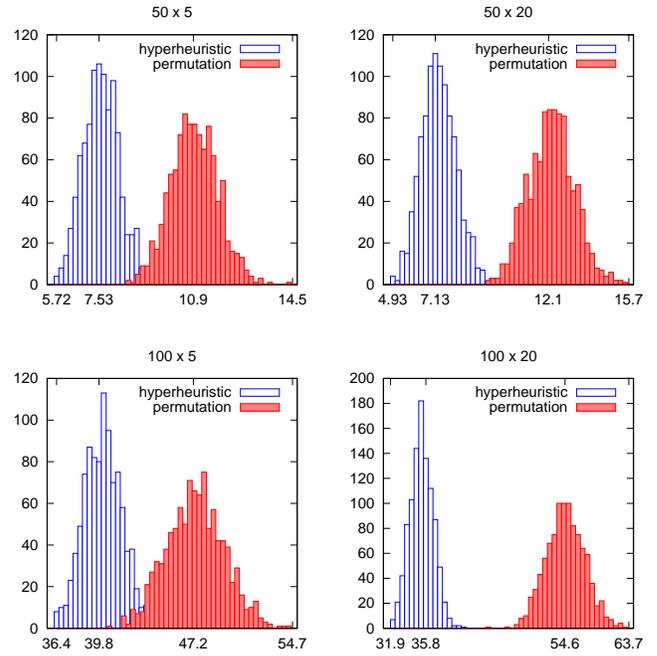


Fig. 3. Distribution of $sumWT$ values of random solutions of the hyperheuristic and permutation spaces

2) *Neighborhood of the best obtained heuristic sequences:* In order to gain information about the ruggedness of the landscapes, Figures 4 and 5 illustrate the mean C_{max} and $sumWT$ values, respectively, (with 95% confidence interval) of all the 1-move neighbours of the best-known solution for each objective function. The horizontal axis denotes the position in the sequence, considering the elements from left to right, whilst the vertical axis the objective function value. A point in the plots with abscissa i represents the mean objective value of all the direct neighbours of the best-known sequence, which differ from it in position i . Since there are 13 low-level heuristic in the heuristic space, each point in the plot represents, therefore, the average cost of 12 other sequences (each having a different heuristic in position i). These plots illustrate two interesting features of these heuristic landscapes. First, the landscapes are rugged, in that small differences in the heuristic list (1-moves) may produce a large difference in the solution objective value. Second, there is a strong positional bias in the heuristic search spaces, where changes on the list left-most positions have a much higher impact on the objective function as compared to the right-most positions. This relationship between the position in the list and the deterioration in cost is steady for the $sumWT$ objective function (Figure 5), whereas for the C_{max} function the relationship (Figure 4) is less structured but still has a decreasing trend. Another interesting observation is that some positions, especially with respect to the C_{max} objective function (Figure 4), are neutral in that their modification do not produce changes in the cost value. These neutral positions tend to be located towards the right end of the sequences (Figure 5).

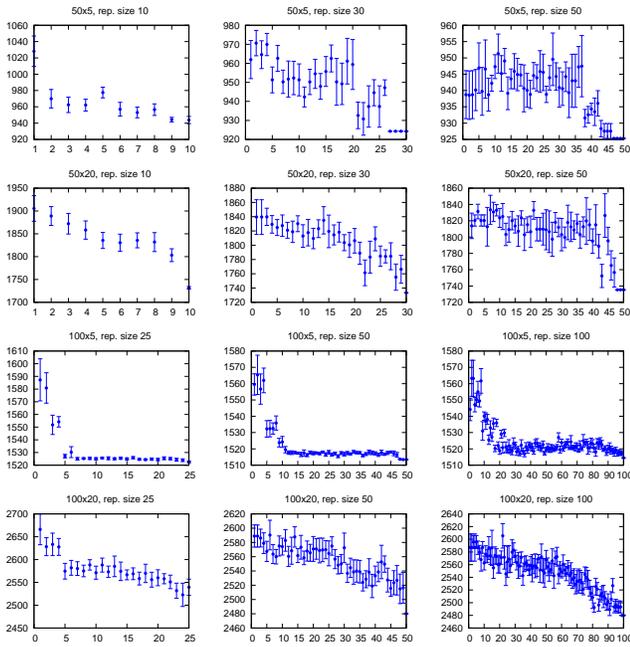


Fig. 4. Mean and 95% confidence interval of the variation in the C_{max} value of the all the 1-move neighbours of the best-known sequence. A point in the plots with abscissa i represents the mean cost of all the direct neighbours of the best-known sequence, which differ from it in position i .

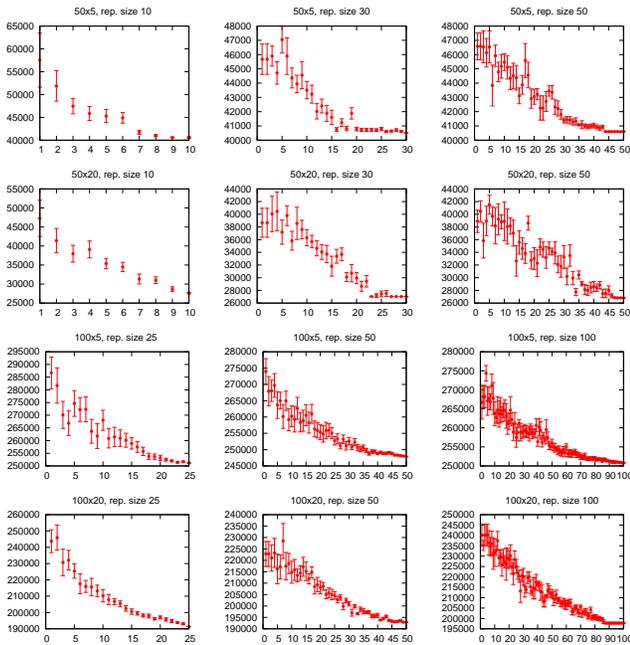


Fig. 5. Mean and 95% confidence interval of the variation in the $sumWT$ value of the all the 1-move neighbours of the best-known sequence. A point in the plots with abscissa i represents the mean cost of all the direct neighbours of the best-known sequence, which differ from it in position i .

B. Fitness-distance correlation analysis

The fitness-distance analysis requires knowledge of the optimal solution. However, given that the optimal solution is not generally known, many studies in the literature use the best-known solution instead. For the analysis, we considered

both a set of random sequences and a set of empirically generated local optima. The set of random sequences were generated as follows. For a given instance, let x^* be the best-known solution in the heuristic search space, referred to as the optimum and obtained after the experiments reported in Table I. In order to have a wide distribution of distances to the optimum, a fixed number of solutions (10 in our experiments) were randomly generated at each distance i , for $i = 1, \dots, n \times m$, away from x^* . Thus, $10 \times (n \times m)$ random sequences were produced for each instance, representation and objective function. The local optima were produced using a next-improvement local-search algorithm, based on the 1-move neighbourhood, and starting from the set of random solutions described above. As the distance metric between the heuristic sequences, we used the Hamming distance, that is, the number of positions in which two sequences differ. Notice that our low-level heuristics set contains 13 elements $\{h_1, h_2, h_3, \dots, h_{13}\}$, but there is no order relationship between them. That is, h_1 is not farther away from h_{13} than it is from h_2 ; the indexing convention for heuristics is arbitrary. Therefore, Hamming distance is a good metric for gauging the distance between two sequences of heuristics.

TABLE II
FITNESS DISTANCE CORRELATION COEFFICIENT WITH RANDOM SAMPLING (fdc) AND LOCAL SEARCH SAMPLING ($fdcls$). REPRESENTATION ARE SHOWN.

n	m	representation	Cmax		sumWT	
			fdc	fdcls	fdc	fdcls
50	5	10	0.580	0.637	0.618	0.741
		30	0.691	0.585	0.650	0.841
		50	0.760	0.615	0.669	0.841
		permutation	0.483	0.133	0.863	0.775
20	10	10	0.634	0.774	0.802	0.894
		30	0.672	0.699	0.595	0.793
		50	0.680	0.758	0.704	0.862
		permutation	0.180	0.047	0.745	0.674
100	5	25	0.744	0.580	0.533	0.877
		50	0.750	0.577	0.545	0.927
		100	0.909	0.685	0.605	0.922
		permutation	0.195	0.085	0.898	0.788
20	25	25	0.670	0.647	0.648	0.870
		50	0.780	0.811	0.790	0.878
		100	0.787	0.834	0.900	0.939
		permutation	0.483	0.291	0.823	0.664

Table II, illustrates the fitness distance correlation coefficients for both the random sample (fdc) and the local optima ($fdcls$) sample of solutions, with respect to the two objective functions. We may observe that all the hyper-heuristic representations show a high positive correlation between the cost and distance to the optimum for both random sequences and local optima (in the range of 0.580 to 0.927), which predicts an easy search. The correlation coefficients of the permutation representation are, on the other hand, much lower, when considering the C_{max} objective function, as compared to the $sumWT$ function.

With respect to the the hyper-heuristic spaces high $fdcls$ values implies that the lower the cost the closer the local optima are to the global optimum (or best-known solution). It also suggests a big valley structure of the underlying

landscape (as discussed in Section III-A). In addition to the fdc_{ls} coefficients, fitness-distance scatter plots (shown in Figures 6, and 7) provide useful information about the landscapes for both the C_{max} , and $sumWT$ cost functions, respectively. Notice that for the hyper-heuristic representation, the plots for all instances and representation lengths have a similar general outlook: the costs of local optima and distances to the optimum show a clear positive correlation. The scatter plots for the permutation presentation (right-most column of Figures 6, and 7) show a different overall picture. For the C_{max} objective function (Figure 6) there is no observable correlation between the cost of local optima and their distances to the optimum, while for the $sumWT$ function (Figure 7), a positive correlation seems to hold, but only for the best local optima; that is, those with a lower objective function values. There are, in this case, a large number of low-quality local optima that show no clear fitness-distance correlation and are, therefore, randomly located in the search space. Finally, notice that for some instances (i.e. that with $n = 100, m = 5$), the scatter plots suggest that there are several (different) local optima having the same or very similar fitness as the best-known solution, so there seems to be a set of optimal solutions (instead of a single optimum) located in a plateau, which suggest the presence of neutrality in these landscapes.

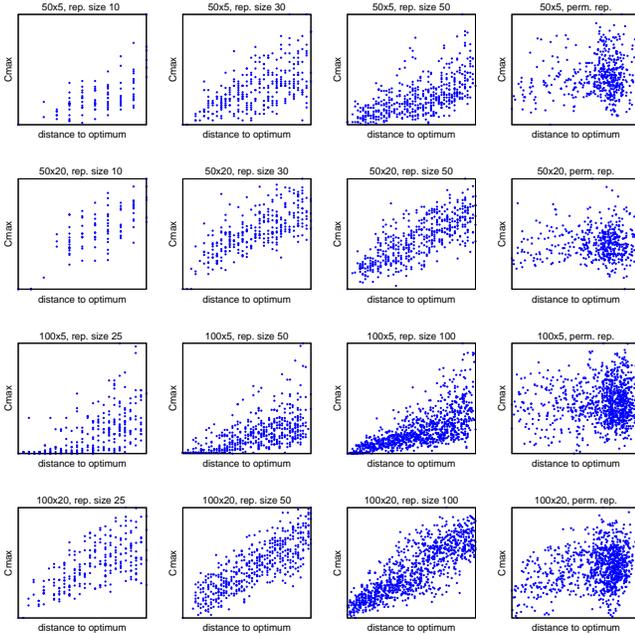


Fig. 6. Fitness-distance correlation scatter-plots of local optima (C_{max} objective function) of the landscapes studied.

VI. SUMMARY AND CONCLUSIONS

Hyper-heuristics approaches differ from other heuristic search techniques in that they operate on a search space of heuristics, rather than directly on a search space of solutions to the underlying problem. Our motivation was, therefore, to study the structure of an example of such

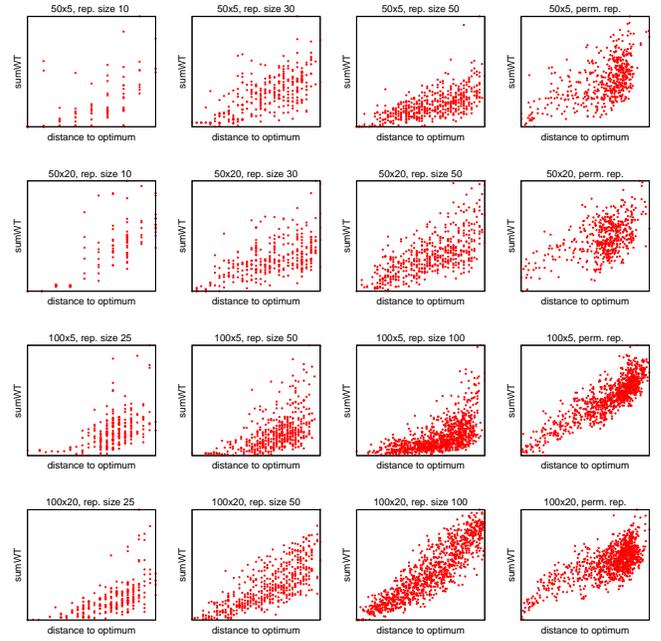


Fig. 7. Fitness-distance correlation scatter-plots of local optima ($sumWT$ objective function) of the landscapes studied.

heuristic search spaces. We formalised the notion of hyper-heuristic landscapes and performed a landscape analysis of the heuristic search space induced by a dispatching-rule-based hyper-heuristic for the hybrid flowshop scheduling problem. This hyper-heuristic operates upon a set of dispatching rules widely used in production scheduling. Specifically, we conducted a fitness-distance correlation analysis of the landscapes of four instances of the hybrid flowshop problem, and employed additional visualisation techniques. We considered two different objective functions, and several hyper-heuristic representation sizes. A permutation based direct representation was also studied for the sake of comparisons. Our study confirmed the suitability of heuristic search spaces, and therefore the relevance of hyper-heuristic approaches. The prominent features of the studied landscapes can be summarised as follows:

- **Big valley structure:** the cost of local optima and their distances to the global optimum (best-known solution) are correlated, which suggests that these landscapes has a globally convex or big valley global structure.
- **Large number of local optima:** the landscapes contain large number of distinct local optima, many of them of low quality.
- **Existence of plateaus (neutrality):** many local optima are located at the same level (height) in the search space, that is, they have the same cost value.
- **Positional bias:** left-most positions in the heuristic list have a much greater impact on the produced solution cost. This implies that the decisions at the early stages of the scheduling process are more important.

We suggest that search algorithms that explicitly exploit the features described above, will enhance the search on this

type of heuristic search space. These performance predictions should be tested in future work. Moreover, similar and more advanced landscape analysis techniques should be conducted on both larger set of instances and types of production scheduling problems.

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