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Approaches to uncertainties in facility layout problems: Perspectives at the beginning of the 21st Century

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Abstract Production uncertainty is one of the most challenging aspects in manufacturing environments in the 21st century. The next generation of intelligent manufacturing is dynamically depending on the production requirements, and success in designing agile facilities is closely related to what extent these requirements are satisfied. This paper presents the most recent advancements in designing robust and flexible facilities under uncertainty. The focus is on exploring the way uncertainty is incorporated in facility design, namely dynamic and stochastic facility layout problems. Recent approaches are explored and categorized in detail, and previous approaches are briefly reviewed in the related categories. Furthermore, research avenues warranting exploration in the emerging field of facility design are also discussed.

Keywords Uncertainty · Dynamic facility layout problem · Stochastic facility layout problem · Robustness · Flexibility

Introduction

This review paper addresses facility design issues under uncertainty which are very likely to appear in today's intelligent manufacturing and service venues due to the higher degree of automation. The importance of the subject and the motivation to write this paper can be summed up by the following fact: As reported in the flagship textbook on Facilities Planning (Tompkins, White, Bozer, & Tanchoco, 2003), in the United States, each year since 1955, about 8% of the gross national product (GNP) has been spent on new facilities, and with the continuous improvement concept that companies have adopted, it is reasonable to assume that more than $ 250 billion is spent for layout or relayout issues annually.

Two excellent review papers (Kusiak & Heragu, 1987; Meller & Gau, 1996) present an overview of research on facility design, namely block layout. An extensive review of uncertainties in manufacturing is performed by Sethi and Sethi (1990). According to this survey, there are two types of uncertainties: the first one is due to internal disturbances, such as equipment breakdowns, variable task times, queuing delays, rejects, and rework, etc., and the second one is caused by external forces, such as uncertainties in the level of demand, product prices, product mix, etc. A classification framework of eleven different uncertainties is given in Table 1. The bold ones have been of primary interest for facility layout researchers in recent years.

By considering future changes in the design step, facility managers can select designs that do not radically degrade with production changes (i.e., robust and flexible facility designs). There are two approaches to designing robust and/or flexible facilities. The first approach, the dynamic facility layout problem (DFLP), considers several production periods, and facility layout arrangements are determined for each period by balancing material handling costs with the relayout costs involved in changing the layout between periods. The biggest difficulty in DFLP has been to estimate future production patterns and condense them into a few discrete scenarios. The second approach is the stochastic FLP in which product mix and demand are assumed to be random variables with known parameters (e.g., expected

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Table 1 Types of manufacturing uncertainties

Component or Basic	System	Aggregate
o Machine o Material handling o Operation	o Process • **Routing** o Product • **Volume** • **Expansion**	o Program o Production o Market

value, variance, covariance and routing information of products and unit material handling costs). The single period stochastic FLP is different than DFLP since product demand is stochastic in the former rather than only subject to known changes from period to period as in the latter.

The rest of the paper is organized as follows: Sections "The dynamic facility layout problem" and "The stochastic facility layout problem" collect a state-of-the-art survey for the DFLP and stochastic FLP, respectively. The solution approaches are also summarized in tables at the end of each section for easy referencing. Emerging research directions are given in section "Research directions", and concluding remarks are in section "Conclusions".

The dynamic facility layout problem

Although the static version of the problem has been widely studied in the literature, Nicol and Hollier (1983; 178) support the necessity of dynamic treatment of the problem by concluding that "radical layout changes occur frequently, and therefore, management should take this into account in their forward planning." The DFLP considers flow over multiple time periods in an environment where material flow between departments changes over time. The DFLP analysis focuses primarily on comparing material handling costs with rearrangement costs (see the formulation of the DFLP in section"Formulation"). A previous state-of-the-art survey which mainly focuses on DFLP algorithms can be found in Balakrishnan and Cheng (1998). This paper herein, however, broadly surveys different types of uncertainty in facility design including the recent developments in this area and introduces emerging research directions as well.

Formulation

In a very general Quadratic Assignment Problem (QAP) form, the DFLP can be expressed as follows by adopting the notation (except N, which represents the total number of departments and locations, instead of n) used in Urban (1998):

$$\text{Minimize} \quad \sum_{t=1}^{T}\left[\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{N}\sum_{l=1}^{N} f_{ikt}d_{jl}x_{ijt}x_{klt} + \sum_{i=1}^{N} s_{it}y_{it} + r_t z_t\right]$$

Subject to

$$\sum_{i=1}^{N} x_{ijt} = 1 \qquad \forall j,\ t$$

$$\sum_{j=1}^{N} x_{ijt} = 1 \qquad \forall i,\ t$$

$$x_{ijt},\ y_{it},\ z_t \in \{0,\ 1\} \quad \forall i, j,\ t$$

where f_{ikt} is the material flow between departments i and k in time period t, d_{jl} the distance between locations j and l, s_{it} the variable rearrangement cost of moving department i at the beginning of period t, r_t the fixed rearrangement cost of making any rearrangement at the beginning of period t. x_{ijt}, y_{it}, and z_t are decision variables as follows:

$$x_{ijt} = \begin{cases} 1 & \text{if department } i \text{ is assigned to location } j \\ & \text{in period } t \\ 0 & \text{otherwise} \end{cases}$$

$$y_{it} = \begin{cases} 1 & \text{if department } i \text{ is relocated at the beginning} \\ & \text{of period } t \\ 0 & \text{otherwise} \end{cases}$$

$$z_t = \begin{cases} 1 & \text{if any rearrangement is made at the beginning} \\ & \text{of period } t \\ 0 & \text{otherwise.} \end{cases}$$

Solution methods

Different solution approaches for the DFLP are grouped into four categories: exact methods, heuristics, metaheuristics, and hybrid approaches. Following detailed explanations about each study, Table 2 is included for easy referencing. (Nine out of 24 papers in Table 2 have been published after Balakrishnan and Cheng's (1998) survey paper on the DFLP.)

Exact methods for DFLP

Pioneering work in dynamic facility layout was undertaken by Rosenblatt (1986). A deterministic environment is assumed, where product demands are known for each period. The major goal is to decide on the layout for each period given the from-to flow matrices. Rosenblatt develops both optimal and heuristic procedures based on dynamic programming (DP) where the objective is

Table 2 Different approaches for the DFLP

	Methods							
	Exact		Heuristics		Meta-heuristics		Hybrid Approaches	
	Approach	Author (Year)	Approach	Author (Year)	Approach	Author (Year)	Approach	Author (Year)
Equal area	Dynamic Programming (DP)	Rosenblatt (1986)	Steepest-decent pairwise-interchange	Urban (1993)	Evolutionary Algorithms - Genetic Algorithms (GA)	Conway and Venkataramanan (1994), Balakrishnan and Cheng (2000), Chang et al. (2002)	DP and a neighborhood search	Erel et al. (2003)
	Upper bounds for Rosenblatt's DP	Batta (1987)	DHOPE	Kochhar and Heragu (1999)	Tabu Search (TS)	Kaku and Mazzola (1997)	DP and GA	Balakrishnan et al. (2003)
	Fathoming process for Rosenblatt's DP	Balakrishnan (1993)	Improved dynamic pairwise exchange heuristic	Balakrishnan et al. (2000)	Simulated Annealing (SA)	Baykasoglu and Gindy (2001), McKendall et al. (2006)	GA and TS	Rodriguez et al. (2004)
	Constrained DFLP	Balakrishnan et al. (1992)					Hybrid Ant Systems	McKendall and Shang (2006)
	Lower-bound procedures	Urban (1992, 1998)						
	Comparing different procedures	Lacksonen and Enscore (1993)						
Unequal area	Linear Programming (LP)	Montreuil and Venkatadri (1991), Montreuil and Laforge (1992)					DP and GA	Dunker et al. (2005)
	Mixed Integer Programming (MIP)	Lacksonen (1994, 1997)						
	Flexible machine layout design	Yang and Peters (1998)						

minimizing the sum of the material handling costs and the rearrangement costs over all periods. Although a bounding procedure is used to reduce the number of possible states, it does not always produce expected reductions. A heuristic procedure can then be used to reduce the search space by only looking at a limited number of good layouts in each period. After Rosenblatt's (1986) paper, Batta (1987) writes a comment on the dynamics of plant layout that establishes a class of possible upper bounds for DFLP. In the theorem, he states that "if the same layout is kept in each time period $t = 1 \ldots T$, DFLP can be solved as static FLP where the from-to flow matrix is obtained by adding the from-to flow matrices in periods $t = 1 \ldots T$." Another comment on Rosenblatt's (1986) model regarding an alternative fathoming procedure to apply which would work best in situations with relatively low rearrangement costs comes from Balakrishnan (1993).

Balakrishnan et al. (1992) extend Rosenblatt's (1986) study by considering the case where a budget constraint exists for layout rearrangement. They propose a new approach to solve the constrained DFLP. As an alternative solution procedure to DP, the simplex based constraint shortest path (CSP) algorithm of Mote et al. (1988) is used to solve the problem. They conclude that CSP performs better than DP in most cases, but if the problem size is small or the constraint is very tight, DP outperforms CSP.

Urban (1992) evaluates the relative performance of different lower-bound procedures for the DP solution of the DFLP. Later, Urban (1998) develops a lower bound dominating all existing bounds for DFLP. First, an optimal procedure for a special case of the DFLP is presented where the arrangement costs are fixed. To solve this problem optimally, an approach similar to Wesolowsky's (1973) incomplete DP algorithm is used. This algorithm first solves QAP subproblems, and since the QAP is NP-complete, heuristic solutions are also introduced. Also, much tighter bounds are developed for the general DFLP where the rearrangement cost is not necessarily fixed.

Different procedures, which have been developed to solve the modified QAP formulation of the DFLP, are compared by Lacksonen and Enscore (1993). They modify five procedures, namely Computerized Relative Allocation of Facilities Technique (CRAFT), cutting planes, Branch and Bound (B&B), DP, and cut trees, and develop a series of test problems to compare the relative effectiveness of these five procedures. The cutting plane algorithm is found to be the best of the five algorithms for all test problems.

By considering expansion (or decline) possibilities, Montreuil and Venkadatri (1991) use a proactive strategy to design dynamic layouts. The method first estimates probable scenarios of system requirements at maturity, then designs an optimal mature facility given the set of scenarios, and finally, by going backwards, obtains an initial facility design.

Lacksonen (1994) describes a two-stage approach to solve the DFLP, which requires a QAP formulation of the problem solved by a cutting plane routine in the first stage and an MIP modeling to find a desired block layout. Then, Lacksonen (1997) further studies this two-stage algorithm by integrating a preprocessing method to predefine certain department pair orientations.

Yang and Peters (1998) propose a flexible machine layout design procedure which formulates and solves a robust machine layout design problem over a planning horizon. It is a construction type algorithm, and it optimizes the trade-offs between material handling costs and machine rearrangement costs to adapt the layout to future changes. The model is not restricted to equal size machines unlike most of the QAP based procedures. The rearrangement cost is assumed to be independent of the distance the machine is moved and is defined as a fixed cost of changing the location of that machine. This approach also differs from previous methods that either assume the rearrangement costs are a linear function of the distance moved (Montreuil & Laforge, 1992) or the number of square-feet being rearranged (Lacksonen, 1994).

Heuristics for DFLP

Urban (1993) proposes a heuristic approach based on the steepest-decent pairwise-interchange procedure for the DFLP. It is a multiperiod equivalent of CRAFT. The procedure avoids the complexity and intense computational requirements of the well-known previous optimal methods, the DP and QAP models. This heuristic performs only slightly worse than optimal procedures, and is as effective as any existing heuristic method. Balakrishnan et al. (2000) propose an improved dynamic pair-wise exchange heuristic based on Urban's (1993) technique. First, they use a backward pass instead of the forward pass in Urban's heuristic because the backward pass will never generate a worse layout than the forward pass. Then, they combine Urban's heuristic with Rosenblatt's (1986) DP procedure. Finally, when they test the new procedure on different problems, in almost every case, they show improvements on the results published by Urban (1993).

Kochhar and Heragu (1999) develop an algorithm, Dynamic Heuristically Operated Placement Evolution (DHOPE), for the multi-floor DFLP. Given a layout for the first period, DHOPE attempts to find a layout minimizing the sum of material handling costs and rearrangement costs for the second period. If the objective is to find a near-optimal layout for two consecutive periods given the material flow information for both periods at the initial design step, DHOPE finds these layouts in two iterations. By doing so, DHOPE finds the best combination of layouts for the two periods.

Meta-heuristics for DFLP

Three well-known meta-heuristics, namely Genetic Algorithm (GA), Tabu Search (TS), and Simulated Annealing (SA) have been applied as solution procedures for the DFLP.

i) Genetic Algorithm (*GA*): Conway and Venkataramanan (1994) use GA for the CDFLP with a budget constraint on rearrangement of the departments. This approach can deal with multiple and nonlinear objective functions as well as side constraints. They test their algorithm on two different problems and conclude that the GA approach performs well in comparison to DP for the six and nine department problems, though no computational times are given.

Balakrishnan and Cheng (2000) also develop a very similar GA approach to the one which Conway and Venkataramanan (1994) have used. Balakrishnan and Cheng's procedure differs in three aspects: (i) a point-to-point crossover operator is used instead of a single point crossover to increase the search space, (ii) mutation is used to increase the population diversity, and (iii) a "generational replacement" approach is used to increase population diversity. The results show that Balakrishnan and Cheng's (2000) GA performs better than Conway and Venkataramanan's (1994) GA. The difference in performance of the two GA approaches is more significant for larger size problems.

Chang et al. (2002) use a Symbiotic Evolutionary Algorithm (SymEA), which differs from a canonical GA approach, to solve DFLP. Instead of using a crossover operation, they use a multi-population approach where there is a population for each period, and populations are evolved simultaneously. It has been shown that SymEA outperforms previously published GA results for the DFLP.

(ii) *Tabu Search* (*TS*): Another meta-heuristic approach for DFLP is TS by Kaku and Mazzola (1997). In their local neighborhood search, they use pairwise interchange moves between departments. Their TS heuristic is a two-stage procedure. In the first stage, a number of different starting solutions are generated using a diversification strategy to ensure that different regions of the search space are explored. In the second stage, neighborhoods around the best solutions found in stage 1 are searched more intensively. At the end of stage 2, the best solution obtained for the problem is the final layout found by the TS heuristic. Computational experiments show that the TS solutions are at least as good as the best solutions found by the different algorithms in Lacksonen and Enscore's (1993) study.

(iii) *Simulated Annealing* (*SA*): Baykasoglu and Gindy (2001) develop an SA approach to the DFLP. In all problems they study, the departments are assumed to be of equal shape and size. The results indicate that, especially for larger size problems, the proposed SA approach outperforms the two earlier GA approaches.

Later, McKendall et al. (2006) develop an SA approach to the DFLP and solve the problems with the data sets taken from the literature. In most of the cases, the proposed SA procedure is the preferred heuristics compared to the previous GA or SA procedures.

Hybrid approaches for DFLP

Erel et al. (2003) propose a new hybrid algorithm with three phases. First, viable layouts, which are the layouts likely to appear in the optimal solution to the DFLP, are selected. Second, a shortest path problem over the viable set found in the first phase is solved by DP. Finally, DP solutions in the previous stage are improved with a local improvement procedure. Computational experiments yield the results, showing that the new procedure is at least as competitive as the previous GA and SA based procedures

Being aware of the reality that exact solution approaches are not practical for large problems, Balakrishnan et al. (2003) develop a GA based hybrid algorithm. In the proposed hybrid method, initial population is obtained using Urban's (1993) method, the crossover operator uses DP to find the best combination among all the layouts, the mutation operator uses Armour and Buffa's (1963) improvement-type CRAFT. They compare the new hybrid method with previous meta-heuristics approaches. They conclude that the hybrid approach of combining GA and DP provides improvements over GA alone, and it also compares favorably with a previous SA approach.

Rodriguez et al. (2004) develop a hybrid meta-heuristic approach in order to improve the performance of each individual meta-heuristics on the DFLP. In this approach, each offspring generated by the crossover operator of the GA is improved by a TS procedure. The comparisons of the results of the new hybrid algorithm with DP, GA, and GA based hybrid algorithms are quite promising.

Another hybrid algorithm combining DP and GA is proposed by Dunker et al. (2005). The idea and the method of combining DP and GA are very similar to those of Balakrishnan et al. (2003) mentioned above in detail. Unlike the previous similar hybrid algorithm, Dunker et al.'s algorithm can cope with unequal area departments, which may also change from period to period allowing for modeling departmental expansion or shrinkage. Two examples of Yang and Peters (1998) are used to evaluate the quality of the algorithm, and the results show that the layouts found by the hybrid algorithm are an improvement over the previous ones.

McKendall and Shang (2006) apply Hybrid Ant Systems (HAS) to the DFLP. This is the first application of HAS to the DFLP. Three different versions of the heuristics are tried, and results show that the proposed procedures perform well for the data sets taken from the literature.

The stochastic facility layout problem

The second type of uncertainty treatment in facility layout assumes that product demand or product mix is not known deterministically but stochastically. Since different criteria are used as objectives, there is no single formulation for the stochastic FLP. However, different criteria used as objectives are discussed in the next section and are shown in Fig. 1.

Criteria used as objectives

Most stochastic FLP research focuses on two important notions: *flexibility for future changes* and *robustness to uncertainty*. A robust facility is one that behaves well over a variety of scenarios and outcomes. On the other hand, a flexible facility is one that can readily adapt to changes without significantly affecting performance. For example, a layout with some vacant space in strategic locations could be expanded readily and would be flexible if production increased, but it may not be robust. To point out the importance of robustness to uncertainty and flexibility for future changes, an *IIE Solutions* (2001) article, titled "Consortium Works to Design Factories of the Future," quotes Dr. Saif Benjaafar, a seminal researcher in the field: "Relayout can be highly expensive and disruptive, especially when the entire factory has to be shut down and production stopped." In the following sections, the way different researchers use these two notions in optimization will be reviewed. Table 3 is structured to cover the research on the stochastic FLP. (Balakrishnan and Cheng (1998) survey some of the stochastic FLP research in their DFLP literature review, and seven out of 17 papers in Table 3 have been published since then.)

Flexibility

Shore and Tompkins (1980), who are the first to consider facility design under uncertainty, focus on the *flexibility* concept in facility layout under the stochastic environment. They define flexibility as the ability of layouts to respond to current and future product mixes. Then, they present a methodology incorporating flexibility into the facility design phase. They quantify flexibility by defining a facility penalty, a measure of the effectiveness of the adaptability of different layouts to the changing demand pattern of the products.

Gupta (1986) uses simulation to solve the FLP by considering the flexibility concept. Instead of assuming that flows between department pairs are deterministic, he obtains the flow matrices by using Monte Carlo simulation to randomly generate the flow between all pairs of departments. Square shaped and equal size departments are used in Gupta's study. Individual flow volumes are assumed to be independent and normally distributed with known mean and standard deviation. Using the CRAFT heuristic, a layout for each generated flow matrix is derived. Then, for each layout, the distance between all department pairs is computed and the average distances between department pairs over the set of all generated layouts are calculated. Similar to Shore and Tompkins' (1980) definition, the layout with the smallest penalty value is considered the most flexible layout. However, future relayout costs are not considered.

Bullington and Webster (1987) propose a procedure to evaluate layout flexibility based on cost estimation of a future relayout of the facility rather than based on changes in material handling cost. They use this approach to measure *adaptive flexibility* as opposed to measures of *reactive flexibility*, such as those based on material handling cost.

Savsar (1991) develops a simulation algorithm which is used as a general procedure to generate and evaluate different layouts in the flexible stochastic FLP. The objective function in this approach includes a weighted sum of total material handling costs, total closeness ratings between departments, and expected future relayout costs. Therefore, this approach serves to find a layout with both reactive and adaptive flexibilities. Simulation is used to generate random flow volumes, closeness ratings, and possible future layouts to evaluate randomly generated alternative layout designs.

Kulturel-Konak et al. (2004) consider the *product routing flexibility* which results from changes in the design or the demand of products in the stochastic FLP. Therefore, routing flexibility of a layout is its ability to produce a part by alternative routes through the system. Both production uncertainty and routing flexibility

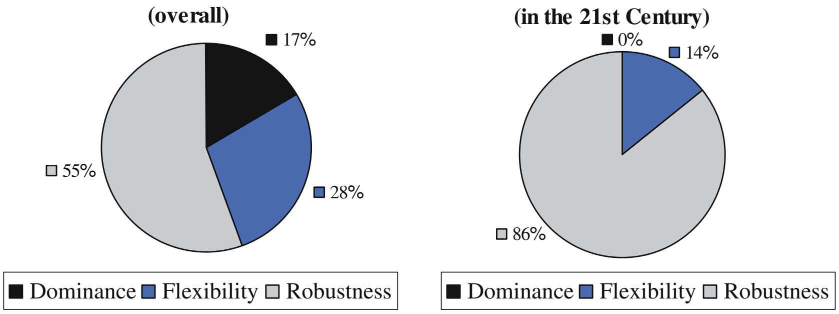


Fig. 1 The stochastic FLP research classified based on the criterion considered

Table 3 Different approaches for the stochastic FLP

	Criteria					
	Flexibility		Dominance (Optimality)		Robustness	
	Approach	Author (Year)	Approach	Author (Year)	Approach	Author (Year)
Equal area	Monte Carlo Simulation	Gupta (1986)	DP (Markov Processes)	Kouvelis and Kiran (1991)	Laplace and Minimax Regret approaches	Rosenblatt and Lee (1987)
	A simple procedure measuring adaptive flexibility	Bullington and Webster (1987)	Weighted average flow matrix approach	Rosenblatt and Kropp (1992)	Branch and Bound (B&B) finding not necessarily optimal solutions	Kouvelis et al. (1992)
	Simulation measuring both adaptive and reactive flexibilities	Savsar (1991)	DP (Markov chain) and heuristics	Palekar et al. (1992)	Integer Programming or a heuristics procedure	Benjaafar and Sheikhzadeh (2000)
					GA and simulation	Azadivar and Wang (2000)
					Fuzzy Theory	Cheng et al. (1996), Aiello and Enea (2001)
					Simulation/flow matrix and analytical approach	Braglia et al. (2003, 2005)
Unequal area	COFAD-F	Shore and Tompkins (1980)			GA	Smith and Norman (2000)
	TS	Kulturel-Konak et al. (2004).			TS	Kulturel-Konak et al. (2004).

are considered concurrently, and an efficient simulation approach to find flow values and a TS based heuristic as a solution approach are developed to find flexible bay structured layouts (Tate & Smith, 1995).

Dominance (Optimality)

Kouvelis & Kiran (1991) incorporate changes in product mix, part routings, and process plans into single and multiple period stochastic layout models. After assigning a probability to each production scenario and developing dominance conditions to determine efficient alternative layouts, a modified QAP formulation (Kouvelis & Kiran, 1990) is used to solve the stochastic single period version of the problem. A DP formulation is also developed for the stochastic multiple-period version of the problem.

Rosenblatt and Kropp (1992) focus on improving an optimal solution procedure for the single period stochastic FLP. They show that their procedure only requires solving a deterministic from-to flow matrix which is the weighted-average of all from-to flow matrices. There are a finite number of possible scenarios which can occur, and for each one, the flow matrices and probability of occurrence of each scenario are known. They also show that the solution of the deterministic version of the flow matrix will result in minimizing the expected material handling cost. Since they randomly generate the probability that each scenario occurs, a simulation model is developed to test the robustness of their approach.

Palekar et al. (1992) solve the stochastic DFLP, which is the most complex of all cases, and all other models can be viewed as special cases of this problem. The stochastic DFLP is formulated as a quadratic integer program. Uncertainties associated with product demands are classified as *optimistic*, *most likely*, and *pessimistic* levels of production for each product and associating a probability of occurrence for these outcomes. Using these estimates, it is possible to create a number of interdepartmental flow matrices for each period, and then, from the probabilities associated with the forecasts, the likelihood of each interdepartmental flow matrix in each period is estimated. Conditional changes from one period to the next one are then modeled as a Markov chain. As an exact method, the DP approach is used. Approximate solution methods have been successfully tested for larger problems.

Robustness

Rosenblatt and Lee (1987) first develop the idea of *robustness* in the single period plant layout problem under stochastic demand. After declaring that finding the exact values of the joint probabilities of the different states is impractical, they suggest representing demand as a three-point random variable, similar to that used in PERT/CPM models. Robustness is defined as the frequency that a layout falls within a pre-specified percentage of the optimal solution for different sets of production scenarios. With this definition, although a particular layout may not be optimal for any given scenario, it can be the most reliable one for all states. They demonstrate the procedure on a small QAP problem.

Kouvelis et al. (1992) also study single and multiple period layout problems under demand uncertainty to find a robust layout. Although Kouvelis & Kiran (1991) deal with the same concept, they are not concerned with robustness, only optimality. Kouvelis et al. (1992) also use the QAP formulation and their contribution is to provide a systematic way to generate robust layouts for single and multiple period problems under demand uncertainty. To do this in a single period case, they simply modify the B&B procedure for the QAP formulation to generate many robust layouts within a pre-specified percentage of the optimal solution for all demand scenarios. With the multiple period case, it becomes more difficult to define robust layouts since relocation should also be considered. The equipment which is difficult to relocate is often referred to as *monument*. Locating these monuments in a way that they will minimally restrict the relayout options is a desired property of a robust layout. They propose a systematic approach which performs well for medium size problems and can be used as a heuristic for larger problems.

Benjaafar and Sheikhzadeh (2000) present an approach for FLP in stochastic environments. In addition to variability of product mix and product demand, duplication of the same department type may be allowed within the same facility. In fact, disaggregation and distribution of a department throughout the facility is not a new idea. Montreuil et al. (1993) introduced the concept of holographic layouts for systems operating in highly volatile environments. A holographic layout allows machines of each type to be spread throughout the facility. Benjaafar and Sheikzadeh have applied this to stochastic environments by allowing for the possibility of partial disaggregation (i.e., each subdepartment may consist of more than one machine and all subdepartments of the same type may not necessarily have the same capacities). Their procedure is scenario-based and the objective is to design a layout that performs well over the set of possible scenarios. The problems are solved either optimally or heuristically. They show that duplicates of the same departments can significantly reduce material handling cost while effectively coping with fluctuations in flow patterns and volumes, although most of the cost reduction occurs with relatively few duplicates.

Azadivar and Wang (2000) solve the FLP by taking into account stochastic characteristics, such as interarrival times of parts into the system and varying part routes, and operational constraints of the system, such as departmental area requirements. They use GA to optimize the layout for manufacturing effectiveness and simulation to evaluate system performance. The proposed approach integrates GA and computer simulation; therefore, this combination is capable of solving very general types of layout problems. However, a costly simulation is performed for each candidate solution which makes the process computationally challenging.

Cheng *et al.* (1996) introduce fuzzy numbers as uncertain flows between department pairs. Then, they solve this hard fuzzy combinatorial problem using GA. Aiello and Enea (2001) also utilize a fuzzy approach to find the robust facility layout in uncertain production environments. A ranking method, which considers the level of decision makers' pessimism, is used to determine the optimal layout.

Taking a different approach, Smith and Norman (2000) study production uncertainty in block layout design with unequal area departments. Uncertainty is measured by an expected value and variance for the forecasted amount of each product to be processed in the facility. The basic concept of their study is the minimization of a statistical percentage of total material handling costs. Since they assume independent products, it is easier to utilize a summation formula. In other words, the probability distribution of the total material handling cost is normal when a large enough number of products are involved. This approach also differs from most of the previous work since it uses the more realistic unequal area formulation. GA is used as an optimization tool.

Braglia et al. (2003) analyze the effects of uncertainties in production rates. Similar to Smith and Norman (2000), they assume normally distributed product demands with expected values and variances. They use simulation to come up with flow values between machines. They focus on finding the most robust layout (i.e., machine sequence). Although the proposed procedure has only been tried on a single row layout, it seems promising on a loop layout. Since they assume independent products, Braglia et al. (2005), in their later work, use the summation of averages and variances of demand variables over the number of periods considered (The Central Limit Theorem). This analytical approach has assisted planners and designers of layouts by suggesting a robust layout.

Kulturel-Konak et al. (2004) study production uncertainty in block layout design with unequal area departments similar to Smith and Norman's (2000) study; however, product demands are not limited to be independent by allowing correlated product demands. Moreover, the product demand can follow any general form and is not limited to certain classes of distributions. Unlike many studies in the literature, which try to optimize for a few discrete scenarios, this study optimizes for all possible scenarios in the predefined continuous range by integrating the robustness function in between lower and upper bounds. TS is used as an optimization tool.

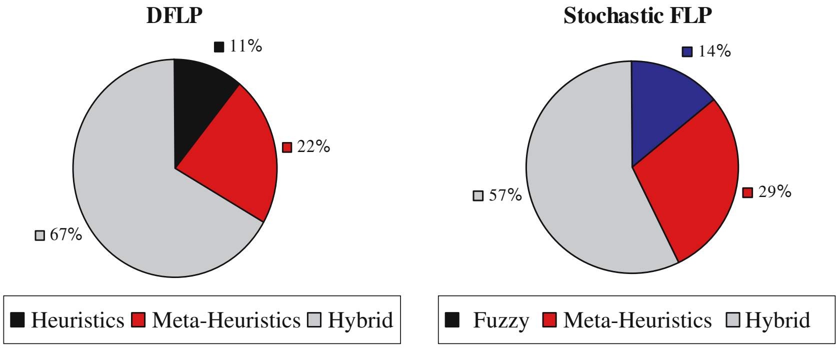
Research directions

So far, this paper has focused on identifying and comparing previous research on uncertainty in the FLP. In addition, these previous efforts have been summarized in two very user friendly tables (i.e., Tables 2 and 3). As can be seen, most previous research efforts are limited in applicability because of the underlying assumptions, such as equal department areas, deterministic flow, or independent stochastic flows. Therefore, at the beginning of the 21st century, the trend is toward relaxing these assumptions and solving problems with unequal departmental area requirements and dependent stochastic product demands. As economies become ever more volatile and product life cycles constantly shorten, incorporating uncertainty in product requirements into facility design models is very important for the applicability of these models in real life scenarios of the global economy. However, such enhancements may require more than simple modifications to the material handling cost function. The challenge is to develop comprehensive stochastic models to capture the dynamics of the global economy. For example, the traditional objective function based on the material handling cost is inadequate to model many scenarios and complexities in the growing service industry. Benjaafar et al. (2002), in "Next Generation Factory Layouts," also assert that most existing layout configurations do not meet the requirements of a volatile production environment, and there is an emerging need to design layouts which are more flexible, modular, and easily reconfigurable. They explore distributed, modular, and agile layouts- the so called next generation factory layout. Their work raises the interesting research question of how to quantify abstract concepts such as modularity and agility of a facility design in the objective functions.

Researchers have also focused on solving bigger-size problems which carry more practical meanings; therefore, Meta-heuristics or hybrid methods have recently been receiving a great deal of researchers' attention. As can be seen from Fig. 2, in recent years, researchers are approaching uncertainty in FLP by using hybrid algorithms (i.e., 67% and 57% of recent work are dedicated to solving DFLP and stochastic FLP, respectively, using hybrid algorithms). Meta-heuristics and hybrid methods, which overcome the drawback of a purely stochastic or deterministic heuristic, also are powerful in terms of incorporating complex objective functions and constraints.

Most of the literature on facility layout focuses on greenfield design, which is a design of a new facility without influence or constraint of an existing facility. In practice, however, the facility relayout problem (FRLP), which is a special case of the DFLP, is more common than the greenfield design since both service and manufacturing industries operate in highly volatile environments which motivate them to redesign their layouts. Nicol and Hollier (1983) surveyed 33 companies of average size, and nearly half of these companies reported that they had an average layout stability of two years or less. Although the greenfield design problem and the FRLP have common characteristics, the FRLP requires additional constraints and objectives. Hence, relayout or reconfigurability began to receive a higher attention in facility layout literature at the beginning of this century

Fig. 2 Solution approaches to DFLP and stochastic FLP



(Heragu, Zijm, van Ommeren,& Meng, 2001; Benjaafar, Heragu, and Irani, 2002). Until then, it has been studied in DFLP research (Kouvelis & Kiran, 1991; Lacksonen, 1994). A slightly different approach to relayout is applied by Lacksonen and Hung (1998). They develop a project schedule where the objective is to reduce the overall cost for relayout. Then, a two-criterion mixed-integer programming model is employed that finds the schedule minimizing costs for rearranging departments subject to precedence constraints. However, recent studies address finding a balance between the material handling and relayout costs and planning for future relayout requirements. Kulturel-Konak, Smith and Norman (2007) address the stochastic FRLP by also prescribing an approach for facility expansion. The facility expansion problem can be simply defined as: given an existing facility and expansion plan, which includes addition of a new department and/or enlargement of an existing one, what is the best relayout of the facility? While rearranging the departments, consideration must be given to the departments with fixed locations such as ovens, furnaces, or receiving/shipping areas. The idea of *fixed departments* is used in the QAP formulation for stochastic FLP (Kouvelis et al., 1992) as follows: once the location of a fixed department is set at the first period, it is not allowed to be changed in the subsequent periods. This approach actually simplifies the problem. In Bozer et al. (1994), a whole department, which is located on the outer perimeter of a plant, is assumed to be fixed and not allowed to be relocated. In Kulturel-Konak et al. (2007), a more flexible and realistic fixed department concept is used. A fraction of a department, which is called a monument, is fixed, and fixed departments are allowed to change shapes as long as they maintain the locations of their monuments. Furthermore, fixed departments can be located anywhere in the layout. Therefore, the previous procedures may need to be applied with more realistic assumptions.

The concept of *block layout*, which deals with sizing, shaping, and locating departments, has received a great deal of coverage in the facility layout and relayout literature. However, due to formulation and computational difficulties, integrated block layout with detailed layout has not been studied well enough. Therefore, the concept of *detailed layout* (i.e., machine placement within each department and selection of location of Input/Output (I/O) points, aisles, and material flow directions) needs to be further investigated while considering uncertainties in facility design, and knowledge based systems or expert systems as discussed in the concept of Intelligent Manufacturing (Kusiak, 1990) might be adopted. It is possible that facilities may respond to changing demand dynamics by modifying the I/O points, aisles, and material flow directions while keeping overall department locations intact. This observation is particularly important for the FRLP. Moreover, the previous algorithms which were developed to handle stochastic demand flows may be applied in different manufacturing environments such as flow shop layout, multi-line layout, semi-circular layout, etc., similar to the work by El-Baz (2004) with static demand flows.

In recent years, there has been increasing attention to the application of mathematical models to solve facility layout problems optimally (Meller, Narayanan, & Vance, 1998; Sherali, Fraticelli, & Meller, 2003; Konak, Kulturel-konak, Norman, & Smith, 2006). Unfortunately, due to the complexity of the problem, these models are only used to solve the static version of the FLP. Therefore, the applicability of the mathematical models when uncertainty is considered in the FLP is an important area to be explored.

Finally, the *stochastic DFLP*, which was studied earlier by Palekar et al. (1992), needs to be further investigated with the recent advancements. Models that account for fixed departments, dependent product demands, and routing and expansion flexibilities in the stochastic DFLP are needed to represent the complex status of real world situations.

Conclusions

With the emergence of a new generation of facility design at the beginning of the 21st century, there is a growing need to configure robust and flexible layouts for both manufacturing and service industries. Therefore, different approaches to the FLP under uncertain environments, namely DFLP and stochastic FLP, were surveyed and categorized, and also listed (in table format) for easy reference. Directions for future research in areas such as the relayout problem, the concept of the detailed layout, the application of mathematical models in the case of uncertainty, and the stochastic DFLP were also discussed.

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