Improving real-life plant performance through layout re-design

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Abstract: Facility Layout Problem (FLP) represents a strategic issue in any manufacturing industry with the purpose of optimizing the overall plant performance in terms of efficiency and effectiveness. FLPs occur each time a company needs to establish a new facility or expand an existing one. Nowadays, the frequent variations in product demand and mix make the layout changeover very intensive. Therefore, the dynamic FLPs, which incorporate the fluctuations expected in the planning horizon while solving FLPs, are considered the best current solution methods. The objectives of the FLPs are multiple, such as to minimize material handling costs and/or waiting times, to maximize revenues and/or service level. Therefore, multiple-objective models were considered increasingly important in the recent years. Nevertheless, the attempt to solve dynamic multi-objectives FLPs brings extremely high computational complexity, with a formulation of extremely challenging and time-consuming problems. Notwithstanding the importance of this issue, there is a lack of literature related to the empirical application of these methodologies that are often assessed by means of mathematical samples. Moreover, most of the studies address FLP only in one stage i.e. the inter-cell layout within the shop floor. Nevertheless, there is another important stage to consider within complex industrial realities, i.e. the intra-cell layout within each cell. This study aims at filling these gaps providing a method to solve real-life inter- and intra-cell FLP, assessing the solutions by applying a multi-objective and dynamic perspective. The proposed method combines one of the most applied heuristic approach (Computerized Relative Allocation of Facilities Technique, CRAFT) and discrete event simulation, widely known as a successful decision support and research tool. CRAFT algorithm solves FLP generating layouts to reduce the amount of material handling within the plant. The layouts generated are assessed by simulation through the objectives, such as the amount of resources involved, production throughput, and buffer size. The paper shows the application of the method within an industrial context, demonstrating its applicability and suitability within real-world complexity.

Keywords: Facility Layout Problem, Performance improvement, CRAFT, Simulation, Case study

1.Introduction

Facility layout problem (FLP), is the systematic arrangement of the facilities necessary to produce goods or to deliver services within the plant, i.e. machine tools, work centres, departments, manufacturing cells, warehouses, etc. (Drira et al., 2007; Prasad et al., 2014; Kulkarni et al., 2015).

FLPs are related to the optimization of the overall plant performance in terms of efficiency and effectiveness, considering the relationships between facilities and material handling systems (Singh & Sharma, 2006; Prasad et al. 2014; Kulkarni et al., 2015; Hosseini-Nasab et al. 2018). Tompkins et al. (1996), believed that a good solving of FLP can reduce by up 50% the total operating expenses. Moreover, the literature supports the effect of a good facility layout in terms of reducing material handling times, increasing production output with obvious implication on productivity, but even arising production flexibility etc. (Yang and Kuo, 2003; Vaidya et al., 2013).

Solving FLPs is not rare for manufacturing or service industries, as it is very unlikely that material flows between facilities remain unmodified during a long planning horizon (Hosseini-Nasab et al., 2018). FLP should be solved every time an organization decides to establish a new facility, but even to expand or modify its actual layout system (Roslin et al., 2009). Nowadays, the pace at which companies should adapt the design of facility layout to new market needs is growing (Bozorgi et al., 2015). The need of flexibility is increased together with the necessity to consider possible changes in the material flow over multiple periods during the planning horizon (Drira et al., 2007; Hasan et al., 2012). Therefore, focusing on dynamic FLPs, that incorporates dynamic aspects with a continuous assessment of the fluctuations in product demand or other problem parameters with respect to time horizon (Kulkarni et al., 2015), is now more important than ever (Hosseini-Nasab et al., 2018).

FLPs represent a strategic issue in any manufacturing industry, with the purpose of optimizing different objective functions, e.g. to minimize costs and/or waiting times, to maximize revenues and/or service level, etc. (Farahani et al., 2010). Therefore, a single-objective is little realistic and suitable to solve real-life FLPs, that take multiple criteria into consideration and trade-off among multiple objectives (Drira et al., 2007; Prasad et al, 2014; Hosseini-Nasab et al. 2018).

While the attempt to solve dynamic multi-objectives FLPs has been demonstrated as one of the best and most realistic solution for real-world FLPs, it brings extremely high computational complexity, with a formulation of extremely challenging and time-consuming problems (Hasan et al., 2012). Moreover, according to Hosseini-Nasab et al. (2018), literature on FLP has often overlooked real-world problems characteristics. Consequently, developing a methodology for solving dynamic multi-objectives FLPs characterized by low computational complexity and test it through a case study would provide a contribution to literature on FLP. Moreover, very little has been done on inter-cell and intra-cell layout problems (Chan et al. 2008). On the other hand, intercellular and intra-cellular movement of parts is known as important and addressing to this aspect would be valuable for literature on FLP.

This study aims at filling these gaps providing a method to solve real-life inter- and intra-cell FLP, identifying the problem solution by applying a multi-objective and dynamic perspective. The proposed method combines one of the most applied heuristic approach, Computerized Relative Allocation of Facilities Technique (CRAFT), and discrete event simulation, widely known as a successful decision support and research tool (Cigolini and Rossi, 2004) that have been successfully combined with other methods to overcome their limitations, such as investment appraisal techniques (Pozzi et al., 2015). This approach is relevant and significant since it considers simultaneously different objectives to optimize, and takes into account all the possible changes that can interest the production system over years, while considering realistic constraints typical of the real-world application. Moreover, the approach provided in this work has been applied to a real production plant demonstrating its suitability and effectiveness in existent industrial contexts.

The next sections of the paper are organized as follows. In section 2 a literature review about FLP is presented to provide a clear view of the framework the present paper refers to. Then, in section 3, the methodology proposed for solving FLP is described. In section 4, such approach is applied to design the layout of the Chinese plant of an Italian company of original equipment for the automotive sector. Finally, in section 5 concluding remarks are drawn.

2.Literature Background

The FLP can be formulated in different ways, but it is mostly theorized in the literature as an optimization problem (Ertay et al., 2006). Koopmans and Beckman (1957), among the first to address studies to the FLP, formulated this problem as a Quadratic Assignment Problem (QAP). QAP aims to define the best location of n departments to n locations minimizing the total material transportation cost between facilities (Liggett, 2000; Sha & Chen, 2001; Bozorgi et al., 2015). This is a discrete optimization (Aleisa & Lin, 2005) and represents the simplest way to model and solve the problem with the assumptions that all departments have equal areas and shapes (Prasad et al., 2014; Bozorgi et al., 2015). An extension of the discrete QAP is founded on Mixed Integer Programming (MIP). The MIP-based methods use a continual formulation for representing layout, in which facilities are placed anywhere and must not overlap each other (Drira et al, 2007). Although MIP-based methods are promising and commonly used in the operations management field, few works use them for dealing with FLP, since they can figure out the optimal solution only for small size FLP (six or less departments according to Singh & Sharma, 2006).

Several research streams were addressed to figure out methods for solving FLP as a QAP and several approaches were identified. The approaches to solve FLP differ one from another based on the type of the problem addressed and on the criteria used to generate and evaluate solutions (Liggett, 2000; Drira et al., 2007). The simplest approaches used to find a solution for FLP are the exact approaches based on mathematical modelling, like branch and bound methods. They are normally used to find optimal solution but only for solving small or greatly restricted problems with a size of 15 or less facilities (Singh & Sharma, 2006; Karagiannaki & Oakshott, 2006; Drira et al., 2007).

QAP belongs to a class of mathematical problems named NP-complete problems, meaning that there are no known methods to find an exact solution of large problems (15 or more facilities) in a reasonable amount of time (Ertay et al., 2006). However, several heuristic and meta-heuristic methods exist, able to generate good suboptimal solutions to realistic sized problems, with high quality outcomes (Liggett, 2000; Sha & Chen, 2001). With reference to heuristic methods, they can be categorized into two main classes. The first one is the construction approaches class, the simplest and oldest heuristic methods to solve FLPs formulated as QAPs belong to it. These methods do not require any starting layout, since they produce solutions from scratch (Singh and Sharma, 2006) through n-stages decision process. They build progressively the solution locating facilities step-by-step, until a complete layout is obtained. Construction approach is like a "search tree" that takes a location decision at each branch, based on the relationship among the different departments or more sophisticated criteria (Liggett, 2000). These approaches have been revealed by the literature as "generally not satisfactory" (Singh and Sharma, 2006). In this class popular algorithms as CORELAP and ALDEP are included. The second one is the improvement approaches class. The methods belonging to this class start from an initial feasible solution (i.e. an initial layout) and try to incrementally improve it. The approach optimizes the operating performance evaluating systematically possible exchanges of the departments and choosing the interchange of facilities that provides the best solution (Liggett, 2000). This process continues until the best solution is found and cannot be improved further (Sha & Chen, 2001). CRAFT, the Computerized Relative Allocation of Facilities Technique, proposed by Armour & Buffa (1963) and Buffa et al. (1964), belongs to this class. It evaluates the department allocation and uses as objective the cost of moving goods along the layout.

Regarding the meta-heuristic methods, they can be categorized in two main classes: the class of global search methods (which includes tabu search and simulated annealing methods) and the class of evolutionary methods (which includes genetic algorithms and ant colony algorithms).

The different solution techniques proposed above can consider single or multiple objectives to optimize. FLPs are related to the optimization of the overall plant performance in terms of efficiency and effectiveness, considering the relationships between facilities and material handling systems (Singh & Sharma, 2006; Prasad et al. 2014; Kulkarni et al., 2015). Tompkins et al. (1996), believed that a good solving of FLP can reduce by up 50% the total operating expenses. Moreover, the literature supports the effect of a good facility layout in terms of reducing material handling times, increasing production output with obvious implication on productivity, but even arising production flexibility etc. (Yang and Kuo, 2003; Vaidya et al., 2013). Nevertheless, most of the existing solving models consider only one objective (mostly to minimize material handling), ignoring many others real-life plant requirements such as to increase production throughput, to decrease production lead times, to minimize WIP, to use spaces properly, to employ machines, manpower, and services suitably (Sharma et al., 2013). Moreover, the complexity of the FLPs increases when these problems are related to the workshop characteristics (Drira et al., 2007). In case of Cellular manufacturing the facilities location and the material handling optimization should be considered within each cell (intra-cell FLP) and within the plant among the cells (inter-cell FLP). This consideration increases complexity and few works addressed the inter- and intra-cell FLPs simultaneously (e.g. Wang et al., 2001; Tavakkoli-Moghaddam et al., 2007; Kumar & Prakash Singh, 2017).

Also, the solving algorithms can be modelled in different ways, considering static or dynamic models. The simplest and traditional modelling and investigation of the FLPs is the static one (Hasan et al., 2012), suitable with stable product demand (Kulkarni et al., 2015) since the layout is assumed to remain constant over a long period of time (Drira et al., 2007) and the material flow is supposed to not change during that planning horizon (Bozorgi et al., 2015). However, today the changes in product demand are increased and the variations in product volume and mix are more frequent than in the past (Benjafaar et al., 2002; Hosseini-Nasab et al., 2018). The market dynamism is growing and the product volumes and mix are changing (Hasan et al., 2012). Therefore, dynamic FLPs (DFLP) are considered nowadays essential for well performing in a long-term period (Arabani & Farahani, 2012), since they permit to have a strong layout under multiple demand scenarios (Benjafaar et al., 2002), minimizing the sum of the material handling and switching costs during the planning horizon (Drira et al., 2007).

An integrated approach of the solution methods explained above with simulation has been demonstrated as useful to consider the dynamic features of the FLPs (Pourvaziri, & Pierreval, 2017). Simulation models are extremely valuable, timely and cost-effective techniques (Karagiannaki & Oakshott, 2006), since they consider both quantitative and qualitative decisions variables (Azadivar and Wang, 2000). Consequently, simulation represents the strongest study to evaluate layouts, measuring the benefits and performance based on real constraints and requirements (Aleisa & Lin, 2005; Drira et al., 2007).

Given the characteristics of the different methodology for solving FLPs summarized by the review of literature, this study proposes an integrated approach based on heuristics and simulation. First, one of the most applied heuristic methods, the CRAFT algorithm, is applied to evaluate different possible solutions to solve the FLP by minimize the material handling inter- and intra-cell. Then, the solutions obtained are assessed by the application of discrete event simulation that selects the best solution based on a dynamic study of the variables (i.e. demand volumes, resources saturation level) that mainly affect the multiple objectives of the study (i.e. the optimization of the performance in terms of production capacity, the optimization of the layout and material handling, the reduction of costs, etc.).

In the following sections the developed methodology and its application to a real case study are explained in detail.

3.Methodology

This study aims to develop a methodology for solving FLP that considers multiple objectives, and which can be efficiently and effectively applied to real contexts. With this aim, a combination of two phases based on different approaches and perspectives is proposed. The former phase deals with the static layout optimization, based on CRAFT algorithm, one of the most applied algorithms to solve this issue. Such improvement-type layout algorithm, starting from an initial (either actual or perspective) configuration of the plant areas, modifies iteratively areas position with the aim of reducing layout cost until no further reduction can be obtained (Armour and Buffa, 1962). A distance-based objective function, in fact, leads to the reduction of cost related to the material flow (Tompkins et al., 2010). The second phase deals with a dynamic perspective, based on discrete event simulation. Simulation is widely known as a successful decision support and research tool (Cigolini and Rossi, 2004) and that have been successfully combined with other methods to overcome their limitations, such as investment appraisal techniques (Pozzi et al., 2015), and is here devoted to improve the resolution of the FLP, evaluating multiple performance indicators (other than the material transport impact, evaluated by the static step) needed for a comprehensive evaluation of the facility layout.

3.1 Static study

To accomplish the static study objective (i.e. the layout optimization based on material flows between facilities) the phase is divided into four steps: (i) data gathering; (ii) design of experiments; (iii) execution of the experiments by CRAFT and (iv) results analysis. The first step of the static study aims at defining data that are relevant to the FLP and that represent the input of the excel "Facility

Layout Add-In” for CRAFT algorithm implementation in MS Excel. Data regards: (a) working and stock areas involved in the material flow and their dimensions; (b) materials flows among the areas and the annual quantities running through them; (c) design constraints. (a) As taking on the FLP not all areas dimensions are available, we here propose how to approximate the dimensions of both warehouse and working areas, depending on the area typology. In the case of a working area, the needed dimension is connected to the space occupied by the resources (e.g. machines, workstations. (b) The materials flows between working areas and stock areas, as well as the annual quantities through them should be collected and organized in a “from-to” chart. (c) With reference to the design constraints, they concern, for instance, with existing minimum and maximum length of the facility dimensions along ‘x’ and ‘y’ axes; need of a single input/output point or separated output points; the weight and the volume of the items to be moved along the paths between areas. As the second step, design of experiments is conducted through the identification of all possible scenarios in terms of layout macro-characteristics. Macro-characteristics are identified by the lengths along ‘x’ and ‘y’ dimensions and by the number of input/output points, according to design constraints. As the third phase, experiments are conducted on as many scenarios obtained by the completion of the second step. All scenarios are implemented in CRAFT, by means of an Excel add-in. The output of the CRAFT implementation for each scenario is given by the layout (i.e. the relative allocation of all the areas) and the related material flow between facilities. The latter is expressed by a measure (hereinafter “logistic work”) taking into account of the distance between areas and quantity flowing through, i.e. the summation, per each link ‘l’ among the areas, of the total annual weight of the items transported through the link ‘l’ (‘Q_l’), multiplied by the length of the link ‘l’ (‘d_l’), as shown in equation (1):

$$\text{Logistic work} = \Sigma\, Q_l\, d_l \qquad (1)$$

Last, the layouts obtained by means of CRAFT are evaluated according to system constraints (e.g. the space available), in order to obtain a feasible layout for the plant (Tompkins et al., 2010). All layouts not consistent with one constraint or more should be discarded and not considered by the dynamic study. Layouts emerged as consistent with constraints should then be evaluated together with the company managers, with the aim to include qualitative considerations that can not be taken into account by optimizing algorithm. Typical observations by managers include the possibility to fit the space with an additional line in one area, in case of an increase in demand, rather than details on the materials distribution and collection policies. The output of the static study is made of the layouts that the management positively evaluates.

3.1 Dynamic study

The objective of the dynamic study is to provide the evaluation of the layouts that represent the output of the static study, through multiple performance indicators and considering them in a future perspective. Moreover, the use of simulation allows extend the study including interaction between the logistic system, i.e. the correct size of the resources characterizing the material handling system, and the evaluated layout.

The simulation-based dynamic phase is grounded on the Simulation Model Development Process (SMDP, see Manuj et al. 2009), already effectively applied in Cigolini et al. (2014). The SMDP consists of 8 steps: problem formulation, dependent and independent variables definition, conceptual model validation, data collection, computer-based model development, model validation, simulation execution, results analysis. Although some steps, such as data collection, have already been performed in the static phase, it is here needed to consider all information that allows studying the dynamic behaviour of the system and that are not considered for the static study. For example, with reference to productive resources, materials management policies, mean time between failure and mean time to repair, are usually needed to simulate the running of the system. Concerning the materials handling systems, technical characteristics, such as resources capacity and availability, are needed to model internal logistics activities.

Regarding the simulations runs, four replications should be performed, while the length of the warm-up periods should be based on Welch’s method.

According to Cigolini et al. (2015), in order to ensure the robustness of the obtained solution to such multi-objectives FLP, the present methodology proposes a dynamic study based on future likely changes in conditions, such as variations in demand or availability of resources.

4.Case study

The proposed methodology is applied to the case of the Chinese plant of an Italian original equipment manufacturer operating in the automotive sector. In the considered plant, raw plastic materials go to the moulding machines department and, from there, plastic components are moved to the input area of the assembly lines. Other components are supplied to the offline subassembly machines area, and, from there, sub-assembled parts go to the input area of the assembly lines. Other materials are supplied directly to the to the input area of the assembly lines, without any previous processing, while packaging materials go directly to the assembly lines output area. Once the assembled product gets out from the assembly lines (output area), they move to the finished product warehouse.

In this context, the FLP deals with the identification of the intra- and inter-cell layout, i.e. the linear or u-shaped position of assembly stations and the relative position of areas (departments and stock areas), that maximizes the production volume (considering 11 millions units as a minimum) and minimizes the number of transportation resources needed, the saturation of operators and the distance, considering a period of one year.

4.1 Static study

Data gathering starts with the identification of the working and stock areas the material flows in between and their dimensions. The materials flow between the identified areas, their dimension (in m^2) and the annual quantities (in kilograms) expected to be running through them are shown in the "from-to" matrix in Table 1.

From area	Area dimension [m^2]	To area Subassembly machines	Upstream area of production lines production lines	Downstream area of production lines	Raw materials warehouse	Final product warehouse	Internal suppliers of plastic components
Subassembly machines	854	0	10,597	0	0	0	0
Upstream area of production lines production lines	954	0	0	141,610	0	0	0
Downstream area of production lines	911	0	0	0	0	36741	0
Raw materials warehouse	1,518	10,597	14,953	5,818	0	0	4,281
Final product warehouse	923	0	0	0	0	0	0
Internal suppliers of plastic components	1,301	0	4,281				

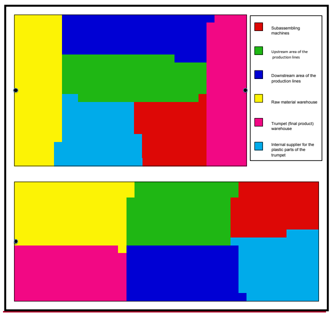
Table 1: "From-to" matrix

With reference to constraints, from a dimensional point of view the maximum width ('x') and length ('y') extensions are equal to 190 and 180 meters, respectively.

Given the data gathered from the field, the design of experiments is aimed at combining ratios of the dimensions of 'x' and 'y' (i.e. 0.5, 1, 1.5, 2) and the number of input/output points of the areas, i.e. whether the intra-cell layout is linear (2 points: 1 input, 1 output) or u-shaped (1 point corresponding for input and output), identifying 8 scenarios to be tested.

The dimensions of the areas are provided as inputs to CRAFT, along with the weights of the links and the characteristics of the scenarios. Given this set of inputs CRAFT elaborates different possible layouts and computes for each of them the logistic work. An example of layouts given as output from CRAFT is provided in Figure 1. The layout in the upper part of Figure 1 represents a linear layout (2 input/output points), while the layout in the lower part represents one of the u-shaped layouts (1 input/output point) provided by CRAFT.

Figure 1: Extract of CRAFT output



In Table 2 the input (x/y, number of inputs/outputs, x and y) to and the output (logistic work) of the CRAFT algorithm are shown. At the static phase, Scenario6 is the best performing as it involves the lowest logistic work amount among all compared layouts. From the discussion with the company, the two alternative numbers of input/output corresponding to the same x/y of the best performing Scenario (i.e. Scenaio5 and Scenario6) are selected to be compared in the dynamic study.

Scenario	x/y	Number of inputs/outputs	x [m]	y [m]	Logistic work [m*kg/year]
Scenario1	0.5	1	64	128	8,290,718
Scenario2	0.5	2	64	128	8,219,889
Scenario3	1	1	91	91	7,138,876
Scenario4	1	2	91	91	3,625,304
Scenario5	1.5	1	111	74	7,079,415
Scenario6	1.5	2	111	74	3,432,527
Scenario7	2	1	128	64	6,952,086
Scenario8	2	2	128	64	3,803,768

Table 2 – CRAFT inputs and output (logistic work)

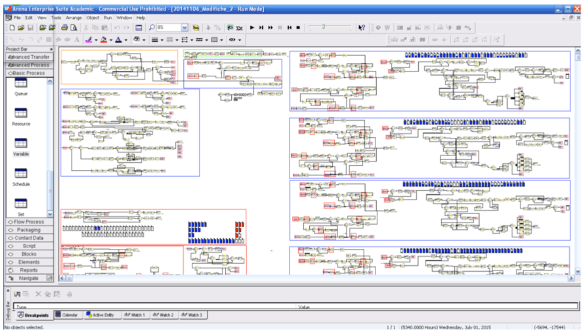
4.2 Dynamic study

In the dynamic study the linear and the U-shaped layouts are compared considering alternative parameters characterizing the material handling systems. In the case studied, the company is implementing a milk-run system in order to go in the direction of lean logistics activities inside the plant. The milk-run deals with transporting little quantities with high frequency to and from the production lines following a kanban scheduling system. Accordingly, supermarkets are considered as stoking point of the production lines that contain materials for a coverage period of production. Accordingly, the alternative parameters are given by: linear or u-shaped layout of facilities, number of picking operators, number of transport resources, transport frequency and re-order point. The annual produced volume is gathered from the dynamic study and considered for benchmarking, while other variables, such as line, picking operators, transport resources saturation values, total covered distance and supermarket volume, are used as additional control variables.

The conceptual model of the system is developed through Petri nets and validated by managers. Based on the validated model, the data needed for simulating the system are collected. The Bill of Materials of the products allows the identification of the components in terms of parts and subassemblies. Each component is described from the point of view of the size and weight, together with the transportation resources capacity. With reference to resources, data about their availability are exploited in the model.

Nine alternative combinations of system parameters are identified and synthetized in Table3. Regarding linear and u-shaped layouts, they differ on the respective presence and absence of transportation resources in the finished product area (i.e. u-shaped layout alternatives perform logistics activities only at one point). Combinations are simulated with Arena simulation software for four times, over a one-year horizon, considering one week as the warm-up period (Figure 2). An order release rate is simulated so that the system should manufacture 11,510,000 units. It is important to highlight, for all alternatives, the simulation model underestimates the saturation of picking operators, overlooking some of the typical picking activities that not differential between alternatives. The average performance values of each simulated combination (benchmark and control variables) are presented in Table 4. As several measures are considered, the management of the company indicates the order of their importance. Among the simulated combinations, number 2 and 7 should be excluded as the produced volumes do not meet the minimum volume requirement (11 million units). The others are all suitable for adoption, while presenting different values of volume manufactured by the end of the time period. Given the highlight on picker saturations, combinations with lower values should be preferred (combination 1, 4, 8 and 9) to the others. Considering the number of operators required by combination 4 (7 operators), this is less preferable than others. Considering the maximum number of pallets as buffer in line, combination 9 is the worst performing, while 1 and 8 are characterized by a lower value.

Figure 2: Extract of Arena simulation model



For these reasons combinations 1 and 8 are the ones considered for the possibility of an increase in demand over the one year period considered. In particular, the case of an increase in order release up to 14 million units over one year is considered. While combination 1 completes the amount, combination 8 is not able to do that and for this reason the best facility layout is the one represented by combination 1 (a linear layout, characterized by a x/y ratio equal to 1.5, 4 picking operators, 2 transport resources, 2 transport missions per hour and 2 hours re-order point).

5.Conclusions

The present work proposes a methodology for inter and intra-cell dynamic and multi-objective FLP, that relies on a static phase and a dynamic one. The first is based on CRAFT algorithm and aimed at identifying possible layouts to be then compared by means of discrete event simulation. To prove the applicability of the proposed methodology, it is applied to the case of the Chinese plant of an Italian OEM. The proposed methodology and its application to a real case provide a contribution to literature on FLP, overcoming the limitations found in the review (i.e. high computational complexity and few applications to real contexts). From a managerial point of view, the methodology represents a useful reference to solve multi-objective inter and intra-cell dynamic FLPs, while the outline of its application to a case study provides useful performance measures to evaluate alternative layouts. The use of a single case study represents the main limitation of the work, that would benefit of additional implementations of the methodology to tests its applicability.

Combination	Layout	# of transportation resources in raw materials area	Transport frequency in raw materials area [times/hour]	# of transportation resources in finished product area	Transport frequency in finished product area hours [times/hour]	Re-order time [hours]	# pickers
1	linear	1	2	1	2	2	4
2	linear	1	1	1	2	2	4
3	linear	1	2	1	2	1	4
4	linear	2	2	1	2	2	4
5	linear	1	2	1	2	2	3
6	u-shape	1	2	-	-	2	3
7	u-shape	1	2	-	-	1	3
8	u-shape	1	2	-	-	2	4
9	u-shape	2	2	-	-	2	4

Table 3 – Characteristics of the simulated models

Combination	Produced volume [units]	Average picker saturation	# operators	Maximum number of pallets as buffer in line	Supermarket space [m^2]	Empty boxes space [m^2]	Total distance covered by transport resources
1	11,508,435	55%	6	7	16.3	3.0	4,028
2	9,697,722	47%	6	7	16.1	3.1	2,834
3	11,167,750	62%	6	7	12.1	3.0	4,014
4	11,501,214	56%	7	7	16.3	3.0	4,028
5	11,507,932	67%	5	7	16.5	3.0	4,002
6	11,484,721	67%	4	9	16.8	3.0	2,415
7	10,733,826	67%	4	9	12.4	3.0	2,415
8	11,484,322	55%	5	9	16.6	3.0	2,376
9	11,484,474	55%	5	10	16.3	3.0	2,363

Table 4 – Performances of the simulated combinations, ordered by importance suggested by managers

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