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# A theoretical background for the reconfigurable layout problem

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**Abstract**

The production system configuration must be able to adapt to varying market demands. The global competition, high product variety and variable volumes require the launch of products with short life cycle and high customization degree. Thus, the approaches to solve this problem should achieve more flexible layouts, while optimizing performance measures. This work presents a systematic literature review of the Reconfigurable Layout Problem (RLP), which has shown potential to satisfy the current manufacturing needs. Specifically, it combines a bibliometric, a network and a content analysis to verify the existence of clusters and the evolution of this subject over the years.


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*Keywords:* reconfigurable layout problem; facility layout problem; systematic literature review; bibliometric analysis; network analysis.

## 1. Introduction

In today's manufacturing environment, flexibility is one of the most important parameters to facility layout design, which is essential for market survival [1]. The flexibility provides the capacity needed to produce several products in the same system and allows the layout reconfiguration, with minimal effort, to meet changes in production requirements, absorbing a high level of uncertainty. The main strategies developed to cope with flexibility issues in the layout design are the dynamic, robust and reconfigurable layouts.

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The dynamic and the robust layout problem concern to find a layout configuration sequence for multiple planning periods and for multiple scenarios and periods, respectively. They assume that production data for those future periods/scenarios are available and consider the costs of switching from one period to the next. These assumptions may turn the layout problem easier to solve, but are unrealistic in many situations. That is because the changes in production requirements usually are unexpected or only known slightly ahead of the next production cycle initiation, making the layout problem more complex, since it should be solved in real time mode [2].

In this context, the RLP emerges, motivated by the fact that many industries (e.g. consumer electronics) have lightweight workstations that can be easily moved, allowing frequent relocation. When workstations and machinery displacement is possible and can be done frequently, the layout problem is significantly simplified. However, it is known that during the relocation process certain degree of losses in production capacity is inevitable [3,4]. Thus, considering reconfiguration costs is important, since a re-layout is only viable when the system relocation costs are low [5,6]. Additionally, the RLP addresses the transition from the current period to the next, minimizing the relocation cost while maximizing the potential saving in material flow and inventory costs [2].

Hence, adaptable processes, equipment and system reconfiguration are challenges that industries face to rapidly respond to market changes, needs and opportunities [7], besides dealing constantly with big data issues of rapid decision making for productivity improvement [8]. This paper carries out a systematic literature review on the RLP to identify its definition, main characteristics, the developments so far and the research gaps of this field of study.

## 2. Reconfigurable layout problem definition and main characteristics

Selecting the best layout configuration is complex and has significant impact on system performance [9]. Then, frequently changing the layout configuration is recommended to deal with manufacturing environments where a high level of uncertainty is present [6,10,11]. In late 90's, the RLP concept emerged to deal with the facility design in dynamic and uncertain environments [12]. A few authors have defined it as a tactical problem [2,13,14], as an optimization problem [5,7,15–21] or, still, as a layout ability of being flexible, movable and changeable enough to adjust its structure due to changes in demand, product mix, volume or other requirements [3,4,6,9–11,22–54]. However, it is agreed that the RLP assumes that production data are available only for current and upcoming production period and considers system operational performance.

In this paper we define RLP as *the ability of the layout to rearrange frequently, with minimal effort, to adjust its configuration to new circumstances, considering system operational performance and providing the exact capacity and functionality needed, when required*. It also aligns for the notion of real-time enterprise, since the changes in the layout configuration should occur rapidly and be readily available, while the production system keeps operating on the edge by doing real-time layout adjustment with live data [2,35]. Also, it is important to consider that during the reconfiguration process some unproductive time may exist, resulting in some loss of production capacity [3,4].

The RLP usually aims to achieve the optimal or near-optimal layout configuration, which quickly allows resources rearrangement to respond to market changes. In addition, the layout should guarantee shorter lead times, lower inventories levels, material flow efficiency and minimum relocation cost, as well as the improvement of system capacity, functionality and performance.

Besides reconfigurability; reusability, responsiveness, adaptability, dynamicity, flexibility, reliability and modularity were considered important features to achieve a reconfigurable layout. The reusability is an economic/strategic factor that allows changing system's capacity and functionality with maximum utilization, while changing product types. It also contributes to the system responsiveness, minimizing underutilized capacity [5,16]. Responsiveness is the system capacity to act in response of sudden changes in market, technology or regulatory requirements. Adaptability, dynamicity and flexibility deal with an existing layout capacity to rearrange quickly and frequently due to changes in the manufacturing requirements. As reusability, they are also connected to the system responsiveness. The reliability aligns to the fact that customers' demand and throughput should be achieved even when a re-layout is in progress. Lastly, modularity is mainly related to software and hardware components, but when the layout problem is focused, the Reconfigurable Machine Tools (RMT) utilization rises, since they are modular machines with a flexible structure that allows changes of its resources, making easier to reconfigure equipment or reorganizing the plant layout. Thus, the modularity facilitates the layout rearrangement in ordinary conditions or when an exception occurs and contributes to resources relocation with minimal effort [24].

## 3. Research method and paper's categorization

This study adopted the systematic literature review, which is a formal approach based on a replicable, scientific and transparent process to locate, select, analyze, synthesize and report evidences [55]. Advantages of using it are many, but increased power and precision in estimating effects and risks worth to be highlighted [56].

The main search engine used was Web of Science that provides a comprehensive citation search and access to several databases. The keywords were defined to obtain scientific papers specifically related to the RLP and to what has been done to solve it. This process resulted in the selection of 60 papers for in-depth evaluation. In order to develop a descriptive analysis of those papers, the following categories were selected: journal, publication year, authors, keywords and cited papers. The analysis provides the statistics for this research area and a comprehension of those papers content.

The selected papers were also classified according to their research method. The categorization was divided into theoretical and practical works. In the first group, there are conceptual papers and literature reviews, while the second group is composed by case studies, modeling and evaluation. The dominant approaches are case studies and modeling, representing 72% of the analyzed papers.

## 4. Initial data statistics

The top 5 journals that most contributed to the RLP (Table 1) indicates that this subject has been studied in production management area as well as in the robotics field of study.

Table 1. The top 5 most contributing journals and the number of retrieved papers.

| Journal | N° of papers |
|---|---|
| International Journal of Production Research | 12 |
| International Journal of Advanced Manufacturing Technology | 5 |
| Computers & Industrial Engineering | 4 |
| Journal of Manufacturing Systems | 3 |
| Robotics and Computer-Integrate Manufacturing | 2 |

Although the RLP concept had emerged in 1994, this work considers papers published since 1998. Fig 1 represents the evolution of this research topic over the years, showing an increasing number of publications.

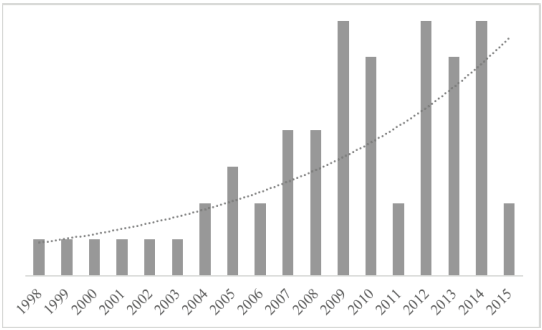


Fig 1. Publishing trend in the RLP area

## 5. Bibliometric analysis

Through the bibliometric analysis, which allows the identification of new fields, activities bursts, bifurcations and mergers [57], the author influence (Table 2 and Table 3) and keywords statistics (Table 4 and Table 5) were

identified. BibExcel was used to conduct it since this application has interaction with several databases (e.g. Web of Science) and software (e.g. Excel and Gephi) [58].

Table 2. The top 10 contributing authors.

| Author | N° of papers |
|---|---|
| Heragu S | 6 |
| ElMaraghy H | 5 |
| Dai X | 3 |
| Meng G | 3 |
| Youssef A | 3 |
| Zijm H | 3 |
| Abdi M | 2 |
| AlGeddawy T | 2 |
| Dou J | 2 |
| Labib A | 2 |

Table 3. The most relevant contributing paired authors.

| Author1 | Author2 | N° of papers |
|---|---|---|
| Heragu S | Zijm H | 3 |
| Meng G | Heragu S | 3 |
| Meng G | Zijm H | 3 |
| Youssef A | ElMaraghy H | 3 |
| Adbi M | Labib A | 2 |
| AlGeddawy T | ElMaraghy H | 2 |
| Dai X | Meng Z | 2 |
| Dou J | Dai X | 2 |
| Dou J | Meng Z | 2 |
| Heragu S | Zijm H | 2 |

Table 4. The most frequently used words in papers title.

| Word | Frequency |
|---|---|
| system | 27 |
| manufacturing | 24 |
| reconfigurable | 23 |
| layout | 15 |
| configuration | 10 |
| approach | 10 |
| design | 9 |
| facility | 7 |
| optimization | 6 |
| dynamic | 5 |

Table 5. The most relevant keywords.

| Keyword | Frequency |
|---|---|
| Reconfigurable Manufacturing Systems (RMS) | 20 |
| genetic algorithm | 5 |
| configuration selection | 3 |
| facility layout | 3 |
| machine selection | 3 |
| optimization | 3 |
| configuration generation | 3 |
| layout design | 3 |
| Reconfigurable Machine Tool (RMT) | 3 |
| simulation | 3 |

The main results of this analysis show that Heragu S and ElMaraghy H seem to be the most contributing authors in this field of study, despite the small number of publications. A deeper examination of their background revealed that the first author has been studying the layout problem in manufacturing systems while the second has been dedicated to study manufacturing systems, in terms of providing them flexibility. Both subjects are relevant to this research topic. A complementary analysis of the paired-author contribution (Table 3) enhances the existence of a research group who focuses on the RLP, in which all the most contributing authors appear. In addition, the small number of influential articles indicates the need for more active research.

In total, 162 different words were considered for paper's title analysis and 122 keywords were counted. When comparing the most used words in paper's title (Table 4) with the most associated keywords (Table 5), it is possible to note the consistence among them and that the 3 most used words in paper's title composes the most used keyword. Besides, the solutions proposals may appear as a keyword. Therefore, it seems that genetic algorithms and optimization models have been the most used methods to solve the RLP.

## 6. Network analysis

The Gephi software was used to conduct a network analysis for the selected sample, due to its functionalities for graph analysis and patterns identification. Also, a citation and co-citation analysis were made to investigate the

connectivity degree between the papers identified in the systematic literature review, considering only the papers that were cited at least two times. The top 10 most referred papers were [2,5,15,59–65], showing their relevance for this field of study.

As result of the network analysis, a co-citation map was established, revealing a 183-node co-citation network. This map is composed by nodes (papers) and edges (paper's co-occurrence). If two publications appear together in the reference list of more than one paper, they are considered co-cited [66]. At first, Gephi randomly locates the nodes, but it offers several algorithms to create different layouts. Force Atlas was chosen due to its simplicity and readability [67]. In this layout, the most connected nodes move to the network center while the nodes less connected move to the borders. The more edges are included, the bigger are the nodes.

The co-citation network also allows data clustering, which has been used in many domains as a classification tool for grouping a given publications set and to investigate community structures in networks. A cluster is a group of well-connected publications that have limited connection to publications in other clusters. The nodes may become a cluster where the connection (weight of edges) is greater between the nodes of the same cluster than when compared to those of different clusters [68]. A default tool in Gephi, based on the Louvain algorithm, was used to identify the clusters of the 183-node co-citation network, establishing 5 clusters. Fig 2 shows the interaction and the clusters' positions..

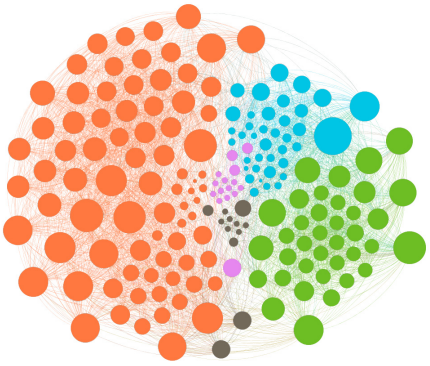

Fig 2. The Force Atlas layout with the 5 clusters representation

## 7. Content analysis of clusters

Based on the papers that compile these 5 clusters, it is possible to define the main research areas, since the papers that are more often co-cited tend to be in the same or in similar areas [66]. The papers contained in cluster 1 have been published since 1975. The earliest papers introduced the concepts of modularity, adaptability and reconfigurability, connecting them to manufacturing systems and its components. Only in late 90's a proper definition of a RMS was made [63]. After that, this type of production system was related as the "key to future manufacturing" [59]. From 2002, the concept of RMT emerged, also the RMS paradigms and the layout design in dynamic environments started to be researched.

Cluster 2 is composed by papers that deals with the traditional layout problem (dynamic and robust), considering restricted or varying areas, multi-floors and other criteria. A few papers have concerned the layout design in changing environments, research challenges and trends. Among the used approaches are heuristics, quadratic assignment algorithms and simulated annealing.

The papers contained in cluster 3 deals with heuristics and metaheuristics in the facility layout design. The leading papers considered dynamic/changing environments and presented a layout performance analysis. It worth to highlight that [2] seems to be the starting point of the RLP research. Cluster 4 includes papers that concerned postponement strategies such as delayed product differentiation as an attempt to simplify the system layout design. Finally, the cluster 5 leading paper presented a decomposition approach to design manufacturing systems. The other articles of this cluster have shown a layout performance analysis, considering productivity and convertibility measures. The number of papers, the main articles and the research focus of each cluster are shown in Table 6.

Table 6. The number of papers, the main papers and the research focus of each cluster.

| Cluster | Nº of papers | Main papers | Research focus |
|---|---|---|---|
| 1 | 70 | [5], [16], [36], [59], [61], [69] | Development of models and strategies to design a RMS |
| 2 | 53 | [7], [60], [62], [70] | Proposals to solve the traditional layout problem |
| 3 | 36 | [2], [71] | Facility layout design using heuristics and metaheuristics |
| 4 | 13 | [72] | Postponement strategies to design the facility layout |
| 5 | 11 | [73] | Decomposition approach to manufacturing system design |

Therefore, besides the fact that the 5 leading papers of cluster 1 are among the top 10 cited papers, the research focus confirms that the cluster 1 tends to be the most relevant group of papers for this research topic, although no cluster focused exclusively in the RLP. As consequence, further investigation is needed to fulfill this gap.

## 8. Methodology and methods analysis

Among case studies, modeling and evaluations, it seems that optimization models, metaheuristics, heuristics and hybrid methods are the main approaches suggested to solve the RLP (Table 7). Mixed integer programming was the optimization model most applied [22,37,50,74], while the genetic algorithm was the most used metaheuristic [2,6, 23,25,29,31,32,34,37,48] and the open queuing network model the most used heuristic [13,75]. Those methods' potential can be exploited in further studies.

Table 7. Summary of solution methods applied to case studies, modeling and evaluation.

| Type | Solution methods | | | |
|---|---|---|---|---|
| | *optimization model* | *metaheuristics* | *heuristics* | *hybrid approach* |
| *case study* | [19], [76], [77] | [11], [23], [25], [29], [31], [32], [34], [41] | [2], [14], [24], [28], [42] | [6], [10], [30], [35], [78] |
| *modeling* | [9], [15], [22], [33], [36], [40], [44], [45], [47], [50], [74] | [3], [38], [52], [79] | [13] | - |
| *evaluation* | [39], [49] | [27], [37] | [75], [80] | [4] |

In general, we can conclude that the RLP objective function is determining the optimal or near optimal layout configuration, but it could consider minimizing costs, maximizing rates, profits or other factors, depending on the manufacturing environment. Additionally, many decision variables have been considered in the problem formulation, e.g., area, demand, batch size, distance between machines, resources/stations number, ramp-up time, cell sizes, operational capacity, immovable machines and costs, mainly material handling costs and relocation costs. Besides, all RLP had some constraints, such as operations sequence or precedence, space for reconfiguration, layout feasibility, unproductive time, departments or machines size and shape, machine capacity, stationary facilities, non-overlapping departments and empty spaces. As consequence of the utilization of many decision variables and constraints, several combinations are possible, resulting in many opportunities for future studies.

All conceptual papers described the facility layout problem, its formulation and solutions developed so far [7,54], while literature reviews addressed a technical analysis and have suggested directions for further research [20,21,26,43,46,51,53]. However, all of them agree that there is a need for more flexible, modular and easily reconfigurable layouts, to adapt quickly to changes in production requirements, after each production period. It was also pointed that the layout problem can be formulated as: discrete; continuous; fuzzy or multi-objective. The most common solution approaches are genetic algorithms, mixed integer programming, particle swarm optimization, simulated annealing, ant colony optimization, heuristic algorithm, neural network and tabu search.

The key conclusions that can be extracted from those papers are that maximizing operational performance is more important than minimizing material handling costs [7]; the reconfigurability paradigm and existing methodologies should be considered to develop new strategies that consider all costs and efforts related to system

reconfiguration [20,21,43]; the use of 3D, graphical tools and approaches such as Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Artificial Intelligence (AI) worth more research to be applied to RMS design, as well as considering risks in the problem formulation [26,46,51,53,54]. Therefore, those are others opportunities for future studies.

## 9. Conclusion

This paper presented a structured literature review about the RLP, establishing it as an important research area. Firstly, the literature was exploited to identify the existing definitions of the RLP and its main features. After, the key contributing authors and journals, the clusters and the main methodological approaches were presented and explored. Finally, an in-depth analysis of the selected sources allowed the identification of trends and gaps. There is available space to the development of hybrid methods (e.g. combining metaheuristics and heuristics) and new strategies, which consider all costs and efforts associated to system reconfiguration, as well as the use of PSO, ACO and AI to resolve the RLP. Graphical tools and available technology (e.g. robotics) may contribute to develop reconfigurable tools and to layout design. Also, considering system operational performance, risk management and reliability measures in the objective function are possibilities for further studies.

However, this study has a few limitations. The bibliometric and the network analysis were conducted to generate insights and to present an objective review of the RLP, identify key papers and key investigators, but they do not provide an interpretation of the papers content or an explanation of their importance to the scientific field. Additionally, the author statistics may not be an effective approach to evaluate the published papers quality, but it can be seen as a positive relation between the quantity and the quality of the key papers. The keywords used in the search were defined to guarantee this study effectiveness, restricting the results to the RLP. As consequence, different keywords utilization may result in a more embracing literature review.

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