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A conceptual framework for integrating Facility Layout and Production Scheduling in Flowshop Manufacturing Cells decisions

Sebastian Cáceres-Gelvez[1]
Martín Darío Arango-Serna[1]
Julián Andrés Zapata-Cortés[2]

1. Universidad Nacional de Colombia
2. Institución Universitaria CEIPA

Abstract

Objective: In this paper, a conceptual framework for integrating production scheduling in flowshop manufacturing cells, known as flowshop group scheduling (FSGSP), and unequal-area facility layout (UAFLP) decisions is proposed. The objective is to define a conceptual model that allows the integration of these important decisions, as well as other complementary decisions, based on a brief literature review. **Materials and Methods**: First, a brief literature review is carried out to identify the elements, solution techniques and complementary decisions for the UAFLP, FSGSP and layout-scheduling approaches. Then, these elements, solution techniques and complementary decisions are described and considered for the definition of the conceptual framework. **Results**: Based on the results of the literature review, a 4-phase integrative model is proposed to integrate the UALFP and FSGSP decisions as well as their complementary decisions so that the sum of the material handling and tardiness penalty costs are minimized for a solution alternative. The phases include the input data collection and preparation process, the definition of the UAFLP, FSGSP and their complementary decisions, the optimization of the decisions when exact, approximate, and artificial intelligence techniques have been applied, and the selection of the alternative with the minimum total costs. **Conclusions**: The integration of these decisions using the proposed framework must be grounded in a lean-manufacturing-based operations strategy whereby the benefits of reducing *mudas*, such as material handling, high work-in-process inventory levels and high machine setup times can be obtained. Finally, the application of this framework, as well as the evaluation of its benefits for a real-world, industrial context can be considered as future research.

Key Words: Conceptual model, flowshop group scheduling, unequal-area facility layout, cellular manufacturing systems, material handling costs, total weighted tardiness, lean manufacturing.

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Autor de correspondencia:

Cáceres-Gelvez, S. (Sebastian):
Maestría en Ingeniería Industrial,
Universidad Nacional de Colombia.
Correo electrónico:
scaceresg@unal.edu.co

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Un marco conceptual para la integración de las decisiones de Distribución de Instalaciones y de Programación de Producción en Celdas de Manufactura de Flujo en Línea

Resumen

Objetivo: En este trabajo se propone un marco conceptual para la integración de las decisiones de programación de la producción en celdas de manufactura de flujo en línea (FSGSP) y distribución de instalaciones con áreas desiguales (UAFLP). El objetivo es definir un modelo conceptual que permita integrar estas importantes decisiones, así como otras complementarias, a partir de una breve revisión bibliográfica. **Materiales y Métodos:** En primer lugar, se realiza una breve revisión bibliográfica para identificar los elementos, las técnicas de solución y las decisiones complementarias para los enfoques UAFLP, FSGSP y programación-distribución. A continuación, se describen estos elementos, técnicas de solución y decisiones complementarias y se consideran para la definición del marco conceptual. **Resultados:** A partir de los resultados de la revisión bibliográfica, se propone un modelo integrador de 4 fases para integrar las decisiones UALFP y FSGSP, así como sus decisiones complementarias, de forma que se minimice la suma de los costos de manejo de materiales y de penalización por tardanza de los trabajos para una alternativa de solución. Las fases incluyen el proceso de recolección y preparación de los datos de entrada, la definición del UAFLP, el FSGSP y otras decisiones complementarias, la optimización de las decisiones cuando se han aplicado técnicas exactas, aproximadas y de inteligencia artificial, y la selección de la mejor alternativa con los costos totales mínimos. **Conclusiones:** La integración de estas decisiones mediante el marco propuesto debe fundamentarse en una estrategia de operaciones basada en la manufactura esbelta mediante la cual se puedan obtener los beneficios de la reducción de *mudas*, tales como el manejo de materiales, los altos niveles de inventario en proceso y los altos tiempos de preparación de las máquinas. Por último, la aplicación de este marco, así como la evaluación de sus beneficios para un contexto industrial real, pueden considerarse como investigación futura.

Palabras clave: Modelo conceptual, programación de producción de grupos con flujo en línea, distribución de instalaciones con áreas desiguales, sistemas de celdas de manufactura, costos de manejo de materiales, tardanza ponderada total, producción esbelta.

1. Introduction

Today’s markets make companies strive to be productive and flexible enough to compete against the customers’ needs for a wide variety of products with short product lifecycles. For this reason, optimizing operations management decisions such as designing an effective facility layout and defining the best production schedule in highly productive production systems, such as the Cellular Manufacturing System (CMS), are key to competing in today's demanding markets (Arango et al., 2012, 2011; Meisel and Prado, 2010; Montoya et al., 2007).

In CMS, production planning is called group scheduling, since groups or families of jobs are formed to be processed on groups of machines called manufacturing cells, to obtain the benefits of group technology applications (Ham et al., 1985; Irani, 1999; Wemmerlöv and Hyer, 1989). When machines in a manufacturing cell are arranged in a flowshop manner, the decision is then known as flowshop group scheduling and is considered one of the key decisions in CMS design and operation (França et al., 2005; Schaller et al., 2000; Wemmerlöv and Hyer, 1989). Flowshop manufacturing cells have a greater impact on production systems by reducing *mudas* ("wastes") due to material handling, work-in-process inventory, and machine setup times, which increases throughput and, consequently, system productivity. The flowshop group scheduling problem (FSGSP) was first defined by (Schaller et al., 2000) and (França et al., 2005), based on the work presented by (Ham et al., 1985). The problem is to find a sequence of part-families and jobs belonging to each family in such a way that criteria based on machine utilization, such as the total completion time of jobs, or customer satisfaction, such as the total weighted tardiness of jobs (TWT), are minimized (Schaller et al., 2000).

On the other hand, facility layout decisions consider the location of departments, workstations, machines or facilities within a floor space while usually reducing material handling costs (MHC), which are known to be one important operating cost for organizations (Drira et al., 2007; Meller and Gau, 1996; Tompkins, 2010). When departments have unequal area requirements, i.e., the dimensions of their sides are different, the problem is known as the unequal-area facility layout problem and was originally proposed by (Armour and Buffa, 1963). The unequal-area facility layout problem (UAFLP) considers a continuous representation of the facility layout where departments cannot overlap, each department must meet the given area requirements and the dimensions of the sides of each department must meet a defined aspect ratio (Komarudin and Wong, 2010; Meller and Gau, 1996). The continuous representation of departments and their unequal area characteristics resembles real-world plant design decisions, thus optimizing this problem facilitates the final facility design process (Balamurugan et al., 2006; Liu and Liu, 2019; Liu and Meller, 2007). Also, an effective facility layout design can lead to the reduction of other *mudas*, such as unnecessary transportation of parts between departments and the travel distance between them, as well as unnecessary personnel movements (Cuatrecasas-Arbós, 2009).

As mentioned before, unequal-area facility layout and production scheduling in CMS decisions are key to competing in today's markets. Despite their potential impact on productivity and efficiency, the integration of these two decisions has not been explored before. (Ripon et al., 2012) proposed a mixed-integer programming model for integrating job scheduling and facility layout decisions and applied a multi-objective approach for solving the model. (Ripon and Torresen, 2014) proposed a hybrid metaheuristic for optimizing the integrated job shop scheduling and facility layout problem. (Wang and Chen, 2008) developed a sequential integrative model for a generator manufacturing case study. The authors used ILOG OPL solver and eM-Plant simulation software for the solution of the problem. (Kazemi et al., 2012) proposed a multi-objective decision-making model and genetic algorithms for optimizing the integrated problem. Other authors have approached the integration of the traditional versions of the problems (Mallikarjuna and Babu, 2018; Ranjbar and Razavi, 2012), however, no author have proposed a systematic integration between unequal-area facility layout and production scheduling decisions in CMS.

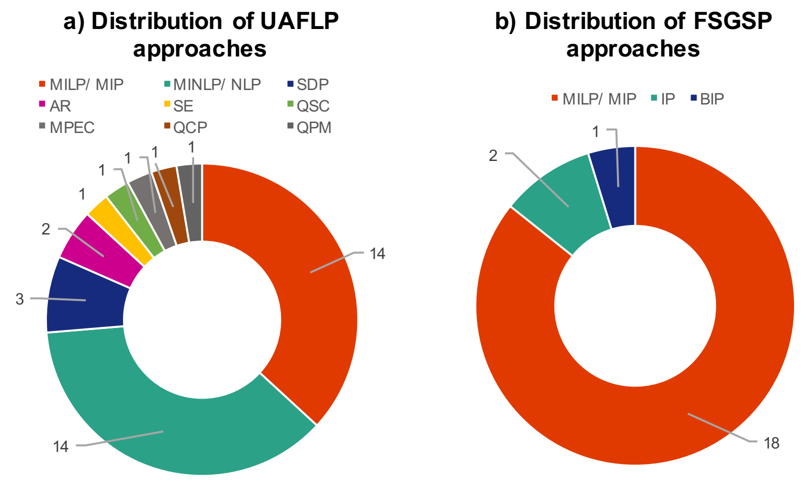
In this paper, a conceptual model for integrating the unequal-area facility layout and the flowshop group scheduling problems is presented. The objective of the article is to present a framework for the integration of these two decisions, based on recent literature on these topics so that future applications can be carried out by organizations to increase productivity and efficiency in their production systems. The model is proposed within a lean environment that seeks to reduce *mudas* such as material handling, through an effective arrangement of departments, and work-in-process inventory and machine setup times, through the manufacturing cell approach. In addition, the integrated decisions seek to minimize material handling costs and tardiness penalty costs, objectives related to rapid response to customers, as well as customer satisfaction.

This paper is divided as follows: first, a brief literature review of the unequal-area facility layout and the flowshop group scheduling problems is presented; then the methods for defining the conceptual model are described; next, the proposed integrative framework is presented and finally, some discussions on this subject are brought up.

2. Literature review

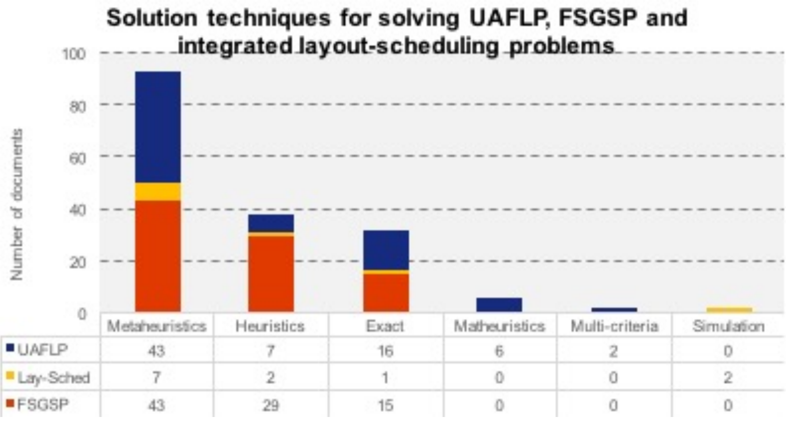
A brief literature review was carried out to identify the elements, solution techniques and complementary decisions of the approaches proposed in the research literature about the unequal-area facility layout, the flowshop group scheduling and integrated layout-scheduling problems. The Scopus database was used to carry out the review, where the keywords "*facility layout*", "*plant layout*", and "*unequal-area*" were used for the unequal-area facility layout problem, "*group scheduling*", "f**lowshop/flow-shop manufacturing cell**", and "*flowline/flow-line manufacturing cell*" were used for the flowshop group scheduling problem and "*layout*" and "*scheduling*" were used for the integrated layout-scheduling problem. The review considered papers from 2000 to April 2021. Figure 1 and Figure 2 presents the results of the literature reviewed for the unequal-area facility layout, flowshop group scheduling, and integrated layout-scheduling problems as they are described below.

Figure 1. Results of the literature reviewed for the UAFLP and FSGSP approaches



Conventions: MILP/MIP: Mixed-integer linear programming, MINLP/NLP: Mixed-integer/Non-linear programming, IP: Integer programming, BIP: Binary integer programming, SDP: Semidefinite programming, AR: Attractor-repeller, SE: Spring-embedding, QSC: Quadratic set covering, MPEC: Mathematical programming with equilibrium constraints, QCP: Quadratically constraint program, QPM: Quasi-physical model. Source: Authors

Figure 2. Solution techniques for solving UAFLP, FSGSP and integrated layout-scheduling. Source: Authors.



	Metaheuristics	Heuristics	Exact	Matheuristics	Multi-criteria	Simulation
■ UAFLP	43	7	16	6	2	0
■ Lay-Sched	7	2	1	0	0	2
■ FSGSP	43	29	15	0	0	0

2.1 Unequal-area facility layout approaches

The unequal-area facility layout problem is an extension of the traditional facility layout problem that considers a continuous representation of departments with unequal area departments. The problem has been widely addressed in the literature due to its complexity.

- *Mathematical approaches:* Different authors have been interested in the presentation of efficient mathematical models that allow an optimal optimization of the problem, either through nonlinear approaches (Alagoz et al., 2008; Allahyari and Azab, 2018; Castillo et al., 2005; Chang and Ku, 2013; Gonçalves and Resende, 2015; Kang and Chae, 2017; Liu et al., 2018), multistage approaches (Ahmadi and Akbari Jokar, 2016; Anjos and Vieira, 2016; Jankovits et al., 2011) and approaches that linearize the exact nonlinear formulation of the problem (Bozer and Wang, 2012; Castillo and Sim, 2004; Castillo and Westerlund, 2005; Konak et al., 2006; Kulturel-Konak and Konak, 2013; Liu and Meller, 2007; Meller et al., 2007; Sherali et al., 2003; Xie et al., 2018). Despite their importance in addressing facility layout decisions, only a few authors considered simulation approaches (Kulturel-Konak et al., 2004; Zhou et al., 2020). Figure 1a showed the distribution of approaches for addressing the unequal-area facility layout decision found in the literature, where mixed-integer programming and non-linear programming formulations stand out.

- *Solution techniques:* Regarding solution techniques some authors have focused their research on developing high-performance metaheuristic algorithms (García-Hernández et al., 2019, 2020b; Komarudin and Wong, 2010; Kulturel-Konak and Konak, 2011; Paes et al., 2017; Palomo-Romero et al., 2017; Salas-Morera et al., 2020; Ulutas and Kulturel-Konak, 2012), as well as matheuristic approaches (Bozer and Wang, 2012; Chang and Ku, 2013; Gonçalves and Resende, 2015; Kulturel-Konak, 2012; Kulturel-Konak and Konak, 2013; Xiao et al., 2016). Other authors have proposed the integration of metaheuristics with expert systems (García-Hernández et al., 2020a, 2015, 2013; Salas-Morera et al., 2020). Multicriteria decision-making methods have also been considered for the solution of the problem (Aiello et al., 2013, 2006). Figure 2 showed the most commonly used solution techniques for the problem, including metaheuristic techniques, exact methods, and the use of heuristic and metaheuristic techniques.

- *Complementary decisions*: The unequal-area facility layout problem was not found to be integrated into other operations management decisions. However, the problem has been considered for solving cellular layout problems in the design of cellular manufacturing systems (Ebrahimi et al., 2016; Houshyar et al., 2016; Salimpour et al., 2021). Additionally, stochastic dynamic extensions of the problem were addressed for flexible manufacturing systems (FMS) where routing flexibility was determined (Seyed et al., 2020).

2.2 Flowshop group scheduling approaches

The flowshop group scheduling problem has been widely addressed in recent years as it is considered a key decision in CMS design and planning (Wemmerlöv and Hyer, 1989). The problem consists of determining a sequence for both the product families and the jobs within each family so that group technology benefits can be achieved.

- *Mathematical approaches:* This decision has been addressed mainly using search approaches (França et al., 2005; Gupta and Schaller, 2006; Lin et al., 2009b, 2009a; Neufeld et al., 2015; Schaller et al., 2000), and more recently through mixed-integer programming formulations (Costa et al., 2020; Gelogullari and Logendran, 2010; Keshavarz et al., 2019, 2014; Lu et al., 2021;

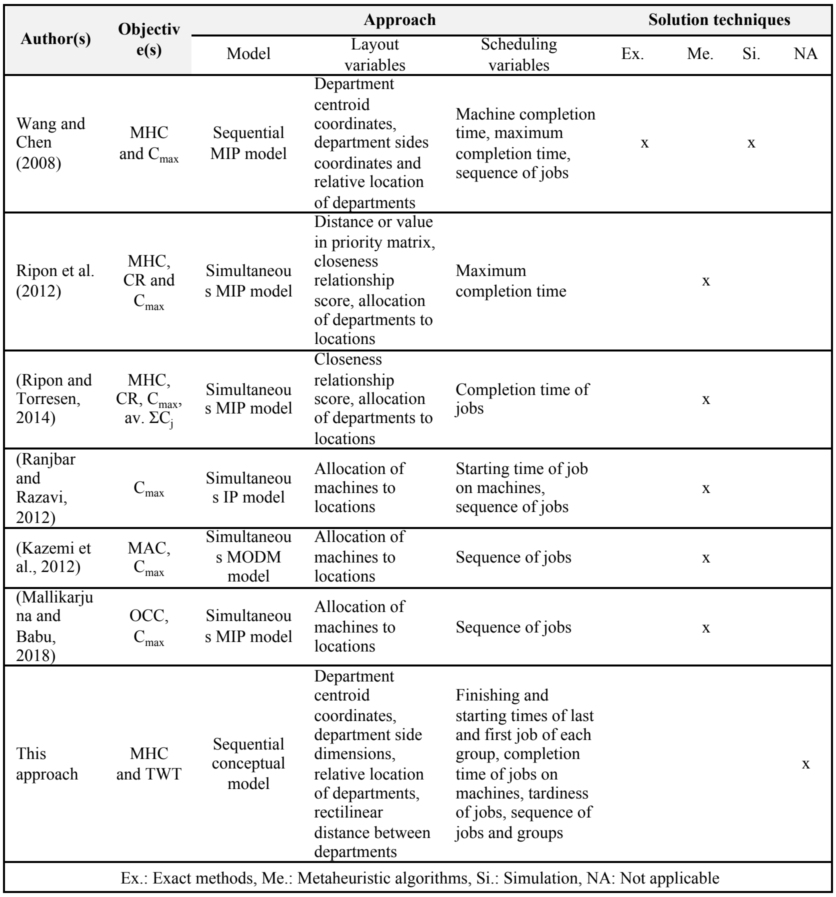
Naderi and Salmasi, 2012; Salmasi et al., 2011, 2010; Yazdani Sabouni and Logendran, 2018; Ying et al., 2012). No simulation approach was found for the problem in the literature reviewed. Figure 1b showed that mixed-integer programming models are more frequently used for addressing the flowshop group scheduling decision as found in the literature reviewed.

- *Solution techniques:* The proposal of exact (Gelogullari and Logendran, 2010; Gupta and Schaller, 2006; Hamed Hendizadeh et al., 2007; Keshavarz et al., 2019, 2014; Lin and Ying, 2019; Naderi and Salmasi, 2012; Salmasi et al., 2010; Schaller, 2005; Schaller et al., 2000; Yazdani Sabouni and Logendran, 2018), heuristic (França et al., 2005; Gupta and Schaller, 2006; Neufeld et al., 2015; Qin et al., 2016; Salmasi et al., 2010; Schaller et al., 2000), and meta-heuristic algorithms (França et al., 2005; Hamed Hendizadeh et al., 2008; Ibrahem et al., 2014; Lin et al., 2009b; Ying et al., 2012, 2010) are frequent for solving the problem. Additionally, the development of hybrid algorithms, i.e. the enhancement of a metaheuristic algorithm using exact algorithms, heuristics, or another metaheuristic, has been also applied to solve the problem (Bouabda et al., 2011; Costa et al., 2020; Khalid et al., 2019; Lin and Ying, 2012; Liou and Hsieh, 2015; Solimanpur and Elmi, 2011). In Figure 2, metaheuristic and heuristic algorithms stand out as solution techniques for solving the decision, followed by the use of exact methods. Matheuristic algorithms were not as frequently found for this problem as when addressing unequal-area facility layout decisions.
- *Complementary decisions:* Flowshop group scheduling decisions can be integrated into a wide range of complementary decisions which include cellular formation and layout (Alimian et al., 2020; Fahmy, 2017, 2016; Kia et al., 2012), other operations management decisions, such as production planning (Ah kioon et al., 2009) and vehicle routing (Mar-Ortiz et al., 2012) and, other advanced manufacturing systems such as reconfigurable manufacturing (Renna and Ambrico, 2015), and flexible manufacturing systems (Balaji and Porselvi, 2014).

2.3 Integrated layout-scheduling approaches

Table 1 presents the current integrated layout-scheduling approaches and solution techniques found in the literature. Most of the papers address the integrated problem using mathematical programming models, where decisions are put together simultaneously and metaheuristic algorithms are mostly applied for their solution (Kazemi et al., 2012; Ranjbar and Razavi, 2012; Ripon et al., 2012; Ripon and Torresen, 2014). However, no approach was found that considers a systematic integration of extensions of these two problems, as well as complementary problems, for operational environments based on continuous improvement philosophies, such as lean manufacturing. The table also shows the objective functions and variables used for the layout and scheduling problems. Material handling costs, as well as the maximum completion time of jobs (*makespan*), are the mainly found objectives while binary variables, such as the allocation of machines to locations within the facility and the sequence of jobs, were more frequently found.

Table 1. Current integrated layout-scheduling approaches in the research literature



Author(s)	Objective(s)	Approach			Solution techniques			
		Model	Layout variables	Scheduling variables	Ex.	Me.	Si.	NA
Wang and Chen (2008)	MHC and C_{max}	Sequential MIP model	Department centroid coordinates, department sides coordinates and relative location of departments	Machine completion time, maximum completion time, sequence of jobs	x		x	
Ripon et al. (2012)	MHC, CR and C_{max}	Simultaneous MIP model	Distance or value in priority matrix, closeness relationship score, allocation of departments to locations	Maximum completion time		x		
(Ripon and Torresen, 2014)	MHC, CR, C_{max}, av. ΣC_j	Simultaneous MIP model	Closeness relationship score, allocation of departments to locations	Completion time of jobs		x		
(Ranjbar and Razavi, 2012)	C_{max}	Simultaneous IP model	Allocation of machines to locations	Starting time of job on machines, sequence of jobs		x		
(Kazemi et al., 2012)	MAC, C_{max}	Simultaneous MODM model	Allocation of machines to locations	Sequence of jobs		x		
(Mallikarjuna and Babu, 2018)	OCC, C_{max}	Simultaneous MIP model	Allocation of machines to locations	Sequence of jobs		x		
This approach	MHC and TWT	Sequential conceptual model	Department centroid coordinates, department side dimensions, relative location of departments, rectilinear distance between departments	Finishing and starting times of last and first job of each group, completion time of jobs on machines, tardiness of jobs, sequence of jobs and groups				x

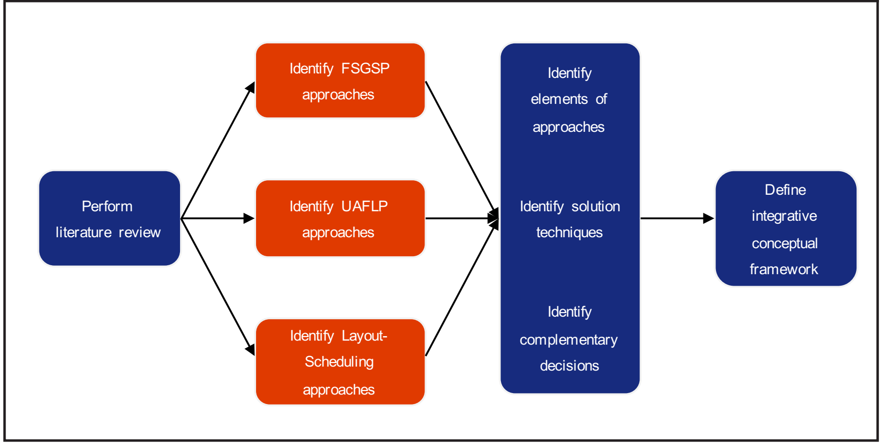
Ex.: Exact methods, Me.: Metaheuristic algorithms, Si.: Simulation, NA: Not applicable

Conventions: MHC: Material handling costs, CR: Closeness relationships, MAC: Machine allocation costs, C_{max}: Maximum completion time of jobs, TWT: Total weighted tardiness of jobs, av. ΣC_j: Average completion time of jobs, OCC: Overall conveyance costs; MIP: Mixed-integer programming, IP: Integer programming; MODM: Multi-objective decision-making. Source: Authors

3. Methodology

The methodology used to define the conceptual framework for the integration of FSGSP and UAFLP decisions is presented in Figure 3. The figure shows the steps taken in this approach, where a literature review was first performed to identify the proposed approaches to the FSGSP, UAFLP and layout-scheduling problems.

Figure 3. Methodology to define the proposed integrative conceptual framework. Source: Authors



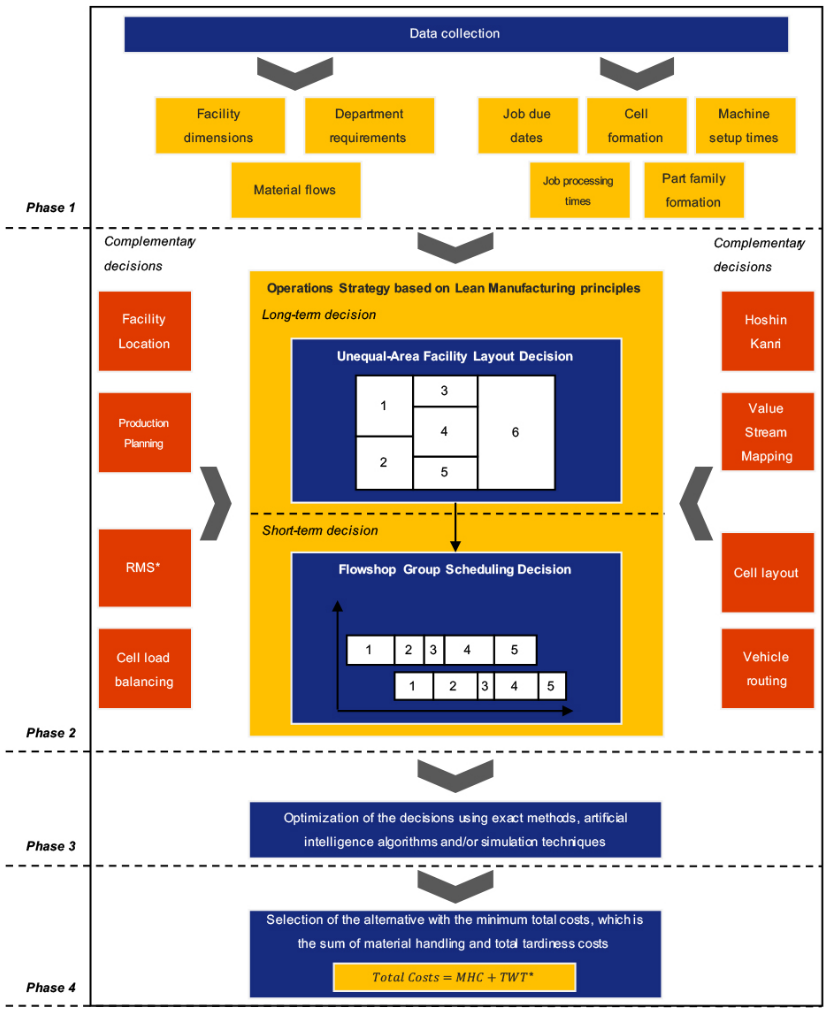
The next step consisted of identifying the elements of these approaches, such as the input data and characteristics of the models; the solution techniques used and the complementary decisions to the problems, such as the cell formation problem, were also identified. Finally, these elements are used to define the proposed conceptual framework for integrating the FSGSP and UAFLP.

4. Results

4.1 The proposed integrative framework

The proposed conceptual model for the integration of production scheduling in CMS and facility layout decisions is presented in Figure 4. The proposed framework is divided into a total of four phases ranging from the collection of the necessary input information to the selection of the alternative with the minimum total cost. Each phase is then comprised of a set of blocks that indicate the elements of the model. The blue blocks indicate the main activities in the proposed integrative framework, e.g., input data collection; the yellow blocks represent the required data for the model and the orange blocks indicate some complementary decisions that can be added to the integrated problem. A description of each phase of the proposed framework is presented below.

Figure 4. The proposed conceptual model to sequentially integrate FSGSP and UAFLP. Source: Authors



* Conventions: RMS: Reconfigurable manufacturing systems, MHC: Material handling costs, TWT: Total weighted tardiness.

4.1.1 Phase 1. Data collection

Phase 1 of the model consists of collecting the necessary input information for the definition of flowshop group scheduling and unequal-area facility layout decisions, according to what was collected in the literature review. At this stage, the context of the application of the model is defined, for example, the case study of a company with productivity problems suffering from high material handling costs, work-in-process inventory, among other *mudas*. For the defined context, the following information is then collected and prepared for the unequal-area facility layout decision, according to exact formulations of the problems (Anjos and Vieira, 2016; Kang and Chae, 2017):

- *Facility dimensions:* Refers to the width and length dimensions of the facility where the production processes are planned to be located. The total area of the facility should be greater than the area requirements of the departments to be located.
- *Department requirements:* They include machinery, equipment, material handling and transportation needs, auxiliary activities, personnel and equipment services, among others. These requirements can be determined based on the plant factors proposed by (Muther, 1973), or using another preferred methodology. In the end, these needs are translated into area requirements for each department, which can be determined using Guerchet's method (Stephens and Meyers, 2013), which considers the definition of a static surface, i.e. machines footprint, a gravity surface, e.g. for the transport of materials, and an evolution surface, for future expansions. Another requirement of the departments is the definition of a preferred minimum aspect ratio for each department, usually given by a value of 1 (i.e. maximum side length equals minimum side length).
- *Material flows:* This information relates to the definition of material and personnel flows between departments. The generation of a from-to matrix for the departments can clarify the material flow requirements.

The following are the pieces of information required for the flowshop group scheduling decision, based on the formulations for the problems as the ones proposed by (Salmasi et al., 2010) and (Naderi and Salmasi, 2012).

- *Job due dates:* Refers to the delivery due dates agreed with customers for the set of jobs (orders) defined for the study. These should be given in the same time unit used for job processing times.
- *Cell formation* and *part-family formation:* To implement the cellular manufacturing system, the process of grouping machines into manufacturing cells and products into product families is carried out so that the benefits of group technology can be achieved. The cell formation problem, as it is known, has been extensively addressed in the literature. See for example (Selim et al., 1998), (Yin and Yasuda, 2006), (Salazar et al., 2010) and (Balakrishnan and Cheng, 2007).
- *Machine setup times:* Refers to information on the setup times required by each machine when processing each of the product families. These setup times may be dependent on the sequence of the product families, for which a changeover matrix is then required to identify this dependency. These times should also be given in the same time unit used for job processing times.
- *Job processing times:* Refers to the running times of each job on each machine, according to the operations required for the assembly or completion of the final product.

4.1.2 Phase 2. Definition of the decisions

Phase 2 of the framework considers the definition of facility layout and production scheduling in manufacturing cells decisions, according to the planning horizon to which they belong. The blocks that comprise this phase are described below.

- *Operations strategy based on lean manufacturing principles:* Since the main objective of the proposed framework is to increase the productivity and efficiency of production systems while reducing waste or non-value-adding activities, the integrative approach must be framed within an operations strategy based on the Lean Manufacturing philosophy. In this sense, the context of the application of the framework must consider the elimination of *mudas*, the focus on customer satisfaction and a culture of continuous improvement as part of its strategy (Cuatrecasas-Arbós, 2009; Dennis, 2015).

- *Unequal-area facility layout decision:* Within the Lean-based operations strategy, the first decision to be defined is the unequal-area facility layout, which is a long-term strategic decision. This is because the decision on the location of departments of a facility responds to a long-term need (1-3 years) to supply a defined demand for given products (Nahmias and Olsen, 2015). In this sub-stage, the input information is used to define the mathematical, optimization or simulation model to be applied for the minimization of the total material handling costs. Exact formulations for the UAFLP, such as the ones used by (Kang and Chae, 2017) or (Anjos and Vieira, 2016), as well as the application of metaheuristic or matheuristic algorithms, such as the ones proposed by (García-Hernández et al., 2020b), (Xiao et al., 2019) or (Kulturel-Konak and Konak, 2013), are suggested in this step. The result is a block layout that defines the location of the departments of the planned facility for optimal or suboptimal material handling costs. This plant layout design can be enhanced using 3D design software such as AutoCAD, SketchUp and Lumion.

- *Flowshop group scheduling decision:* With the formation of product families and manufacturing cells, and using the other input information collected, the model for production scheduling in flowshop manufacturing cells can be defined. Unlike facility layout, production scheduling decisions are considered as a very short-term operational decision, where the sequence of jobs to be processed and their allocation to available resources must be made continuously on the shop floor to respond to customer requirements (Nahmias and Olsen, 2015). However, when there are problems in determining an optimal sequence and, additionally, the wastes inherent to mass production have not been eliminated, the delivery of orders gets tardy, affecting customer satisfaction and the company's image in the market.
  For this reason, it is proposed in this framework to use a mathematical or simulation approach that focuses on minimizing tardy deliveries, especially if they generate a penalty cost that may be given as a contractual clause or as a bad image cost. However, models focused on tardiness minimization are not very popular in the literature. Some mathematical formulations, such as the ones proposed by (Keshavarz et al., 2019), (Yazdani Sabouni and Logendran, 2018) or (Lu and Logendran, 2013), as well as metaheuristic approaches, such as those presented by (Lin et al., 2009b) and (Ying et al., 2010), have addressed this objective. An alternative is to adopt a very efficient mathematical model, such as model 1 proposed by (Naderi and Salmasi, 2012), which was proved very efficient in comparison with model 2, also proposed by the authors, and the model presented by (Salmasi et al., 2010). In these cases, the total weighted tardiness objective function should be included in the model and a constraint defining the tardiness of jobs should be added.

- *Complementary decisions:* The inclusion of complementary decisions to the main problems addressed in this model seeks to increase the robustness of the decisions made at the strategic, tactical and operational levels for the study context. Complementary strategic decisions include the definition of a Lean-based strategy, via the Hoshin Kanri methodology (Hutchins, 2008; Tennant and Roberts, 2001), the identification of value-generating activities in the supply chain, through the value stream mapping (VSM) methodology (Rother and Shook, 2009), and the location or relocation of the facility, using qualitative and/or numerical methods (Zanjirani Farahani and Hekmatfar, 2009), among other complementary strategic decisions. Some complementary tactical decisions considered in the framework are production planning decisions in CMS, as well as the integration of other CMS key planning activities, such as cellular layout definition, cell load balancing and reconfigurable manufacturing systems (Abdi and Labib, 2004; Ah kioon et al., 2009; Singh, 1993). Finally, the integration of operational decisions such as vehicle routing and production control decisions can increase the capacity of the system to comply with customer's requirements (Arango et al., 2014; Gilland, 2002).

4.1.3 Phase 3 and 4. Optimization and selection of the best alternative

The final phases in the proposed framework are phase 3 optimization of the integrated decisions and phase 4 selection of the alternative that minimizes total costs. In phase 3, the preferred technique for solving the problems is selected and implemented, considering the complexity and scope of each of the integrated problems. In phase 3, the preferred techniques for solving the problems are selected and implemented, considering the complexity and scope of each of the integrated problems. In this sense, techniques such as exact algorithms, for example, linear and nonlinear optimization methods; heuristic, metaheuristic, hybrid, matheuristic or artificial intelligence algorithms, as well as simulation software, are recommended for the solution of both UAFLP and FSGSP and their complementary problems (Bozer and Wang, 2012; Keshavarz et al., 2014; Meller et al., 2007; Neufeld et al., 2015; Schaller et al., 2000).

Phase 4 finally compiles the results of the previous phases and selects the alternative with the lowest total material handling and tardiness penalty costs. Thus, the application context of the proposed framework obtains a solution alternative based on lean manufacturing principles, focused on a sequential integration of the unequal-area facility layout and production scheduling in manufacturing cell approaches problems, which minimizes key costs for increased productivity and efficiency.

5. Conclusions

In this paper, a conceptual framework has been proposed for integrating the scheduling decisions in flowshop manufacturing cells and the facility layout decisions for departments with unequal are requirements. First, a brief literature review was carried out where the different approaches, solution techniques and complementary problems for each of these decisions were reviewed and analyzed. The literature review allowed identifying the main mathematical formulations for the unequal-area facility layout (Anjos and Vieira, 2016; Kang and Chae, 2017), the flowshop group scheduling (Naderi and Salmasi, 2012; Salmasi et al., 2010) and the integrated layout-scheduling (Ripon et al., 2012; Ripon and Torresen, 2014) problems. In addition, the results of the review included the identification of metaheuristic and heuristic algorithms (França et al., 2005; García-Hernández et al., 2020b; Palomo-Romero et al., 2017; Schaller et al., 2000), as well as exact methods (Meller et al., 2007; Naderi and Salmasi, 2012; Salmasi et al., 2010; Sherali et al., 2003), as solution techniques for solving these problems. Among these approaches, matheuristic algorithms and artificial intelligence techniques are seen as potential solution tools for future approaches to these problems (Bozer and Wang, 2012; García-Hernández et al., 2013; Salas-Morera et al., 2020). Other operations management decisions, such as cell formation and layout decisions (Alimian et al., 2020; Fahmy, 2016), production planning (Ah kioon et al., 2009) and the design of reconfigurable and flexible manufacturing systems (Balaji and Porselvi, 2014; Renna and Ambrico, 2015), among others, were found to be appropriate as complementary decisions.

The identification of approaches, solution techniques and complementary decisions for the addressed problems was integrated through a 4-phase conceptual framework. The first phase included the collection and preparation of the necessary input data for the industrial context in which this framework is applied. The second phase consisted of the sequential definition of the unequal-area facility layout and flowshop group scheduling decisions, as an integrative approach, based on an operations management strategy focused on lean manufacturing principles. The proposed approach defined the decisions so that *mudas* in production systems, such as material handling, work-in-process inventory, unnecessary movement of parts and personnel, and high setup times of machines, was reduced. For this reason, the total material handling costs and tardiness penalty costs were considered as objectives for the UA-FLP and FSGSP definitions, respectively. Complementary decisions were also included in this phase. Finally, the third and fourth phases considered the optimization of the decisions, using one or more of the techniques found, and the selection of the alternative with the minimum total costs, respectively.

Future research should focus on the integration of systematic and mathematical applications for the integrated framework proposed in this paper. The advantages of CMS and facility layout optimization bring promising benefits in productivity and efficiency indicators for real-world industrial contexts.

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