A Simulation-Based Optimization Methodology for Facility Layout Design in Manufacturing

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ABSTRACT Optimizing production systems is urgent and indispensable if companies are to cope with global competition and a move from mass production to mass customization. The urgency of this need is more obvious in old production plants with a history of modifications, expansions, and adaptations in their production facilities. It is common to find complex, intricate and inefficient systems of material and product flows as a result of poor production facility layout. Several approaches can be used to support the design of optimal facility layouts. However, there is a lack of a suitable generic methodology for designing such layouts. Additionally, there has been little focus on the data and resources required, or on how simulation and optimization can support the design of optimal facilities. To overcome these deficiencies, this paper studies the integration of simulation and optimization for the design and improvement of facility layouts taking into account production and logistics constraints. The paper includes a generic perspective and a detailed implementation. The proposed methodology is evaluated in two case studies and by drawing on the principles and tools of the functional resonance analysis method. This method analyzes the implementation order and variability of a group of processes that can lead to unwanted outcomes. The results can provide managers and other stakeholders with a methodology that adequately considers production and logistics constraints when seeking an optimized facility layout design.

INDEX TERMS Facility layout design, functional resonance analysis method, production and logistics systems, simulation-based optimization.

I. INTRODUCTION

Manufacturing facilities are complex systems to design, maintain, and improve. In manufacturing, between 20% and 50% of the total operating cost is related to material handling; effective facility layouts can reduce this cost by between 10% and 30% [1]. The layout of a system refers to the physical positioning of tasks, facilities, and people relative to each other with the objective of transforming resources. Good facility layout designs will take into account issues of health and security, accessibility, communication between different entities, efficiency, flexibility, clear flows of material and products, as well as fewer transports, less work-in-progress, less used space, and lower cost [1], [2].

The most significant challenges in the design of facility layouts include complexity, dynamicity, randomness, simultaneity, high cost, lack of integration and standard procedures, and safety [3]. These challenges, combined with the large numbers of entities and products in the system, increase the complexity of design considerably.

The main focus of the research reported in this paper is on block layout. Block layout shows the location, shape, and size of areas or departments, without considering the detailed layout within each area (including the exact location of all equipment, workbenches, and storage areas inside each department) [1].

Several methods have been proposed for designing facility layouts. Traditional methods such as construction and improvement algorithms have been commonly applied, allowing systematic planning of the process of designing

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a facility layout. These methods are based on or include well-known facility layout design (FLD) approaches, such as Apple's plant layout procedure, Reed's plant layout procedure, and Muther's systematic layout planning [4]–[6]. However, the complexity of manufacturing facilities today requires the use of more advanced computerized tools for system analysis and design, such as simulation and optimization. A review of traditional and computerized approaches for FLD is presented in section II of this paper. Thereafter, a methodology for the design of optimized complex layouts is presented in section III. An industrial case study is used to explain and analyze the methodology to study its applicability. Finally, the validation approach of the methodology is presented in section IV, and the study concludes in section V.

II. FACILITY LAYOUT DESIGN WITH SIMULATION-BASED OPTIMIZATION

The terminology regarding facility layout or location problems is extensive and sometimes confusing. For example, facility layout problem, facility layout planning, and facility location problem are all referred to as FLP. In this paper, FLP will be used as an acronym for facility layout problem, that is, the problem of the location or positioning of new facilities among existing ones in order to achieve one or more optimization objectives [7].

Facility layout design (FLD) focuses on the process of designing facility or shop floor layouts, that is, arranging the location and distribution of areas or departments in the production area of a manufacturing facility. In this paper, the literature review focuses on FLD methods and particularly on methods supported by simulation and optimization, or combined in simulation-based optimization (SBO). Simulation, in this case, can significantly contribute to manufacturing systems addressing their large scale and complexity. SBO can contribute to the design of near-optimal facilities.

The literature on FLD is extensive, spans several decades, and focuses primarily on the methods and tools used to facilitate the allocation of space in a manufacturing facility. Approaches such as the pair-wise exchange method and the graph-based method have been common in traditional approaches, and now provide a basis for new computerized approaches that can search for optimized facility layout solutions. Many tools are available for these approaches [8], [9]. Exact methods include mathematical optimization modeling, branch and bound and dynamic programming. There are also heuristic algorithms such as construction algorithms, improvement algorithms, the computerized relative allocation of facilities technique (CRAFT), and an automated layout design program (ALDEP). There are also metaheuristic algorithms such as genetic algorithms (GAs), tabu search, simulated annealing, ant colony optimization, and particle swarm optimization (PSO) [8]–[11]. These have evolved with the support of computation and algorithms in which the layout is designed by building a block layout, iteratively adding

departments, and optimizing the distances between them, their shapes, and their area [8].

Recently, several authors have analyzed the development of optimized facility layouts and have proposed a hybrid multi-criteria decision-making approach that includes assigning alternative weights to the variables and objectives of the optimization and using fuzzy logic [12]. Zhang *et al.* [13] used mixed-integer linear programming (MILP) and Lagrarian heuristics to optimize production cost, material handling cost, and space management for a large-scale industrial case study. An additional paper by the same authors used MILP to focus on the location of warehouses in a facility layout [14]. They also proposed a framework of simulation-based methods integrating mathematical algorithms and heuristic methods to balance operational performance and planning cost [15]. Their proposed approaches and framework have contributed to the FLD methodology proposed in this paper.

Other authors have presented additional approaches to manufacturing case studies. For example, Mohamadi *et al.* [16] proposed an optimization algorithm to minimize the distances between facilities and dead space, using a model to obtain information from expert opinions. Due to the complexity considered, they used two metaheuristic algorithms, including PSO and Gas. Zha *et al.* [12] presented a hybrid fuzzy multi-criteria decision-making approach using a combination weights to overcome the limitations due to redundant factors for a facility layout for an aircraft manufacturer. This system also used separate weights and independent relationships between the factors usually considered. Others have applied these improvements in facility layout procedures to manufacturing logistics [2]. Due to the complexity of common logistics systems in manufacturing companies, some authors have proposed combining uncertainty and graph theory for uncertainty reasoning using Bayesian networks to discover the potential relationships between data [17].

Wei *et al.* [18] present a novel approach for facility layout planning optimization with genetic algorithms for reconfigurable manufacturing systems. Their approach is based on chaos genetic algorithms and tent mapping for the generation of the initial population.

Several authors have used simulation to design facility layouts [19]–[21]. Ali Azadeh *et al.* [22] in particular presented an integrated approach using simulation and mathematical programming for the maintenance process of a gas transmission unit. They used simulation to analyze the order of required machining processes. The objective was to minimize the average waiting time of parts and maximize machine and operator utilization. They used fuzzy data envelopment, flexibility, redundancy, and the total cost of every layout combination. Their results showed how the addition of operators and material handling distances affects production. The different steps of their integrated fuzzy simulation approach have been used to construct the methodology in this paper. Zhang *et al.* [23] also propose an optimization approach based on fuzzy demand and machine flexibility increasing the flexibility of the layout considerably.

They state that the inclusion of logistics and reconfiguration in their approach would require the development of a more powerful algorithm. Yang *et al.* [24] propose a modelling method and production configuration optimization for an assembly shop based on discrete event simulation (DES) and GAs.

Optimization can, therefore, be a robust complement to simulation when the systems to be analyzed are large and complex [25]. Its combination with simulation, SBO, can also be an excellent support to FLD when the size and complexity of the problem are considerable, especially in dynamic layouts designs that change over different periods [26]–[28].

In summary, the combination of simulation and optimization and especially the use of DES in this kind of complex manufacturing systems, can support the FLD decision process better than traditional methods if the system is complex and if simulation expertise and tools are available in the organization. DES can provide comprehensive, efficient, and accurate guidance for FLD [24]. Mathematical modeling approaches in manufacturing applications can be a good approach if resources with the required level of competence are available, and if the size and complexity of the layout design are between some boundaries. For example, shop floor shapes, flows of transports, persons or materials should not be complex and the numbers of flows of products or variants should not be too large. Optimization can be a good tool to complement simulation if the number of possible solutions or alternatives is significant, especially when there are a high number of variants to consider and conflicting objectives.

The literature suggests that using SBO in FLD may help manufacturing companies unlock the competitiveness necessary to cope with growing product customization and increasing production flexibility. The utilization of DES is becoming a requirement due to the complexity and scale of the manufacturing facilities. The importance of the integration of internal logistics and material handling systems has also been highlighted. However, there is no generic approach to the design of facility layouts with optimized flows taking production and logistics systems into consideration. This paper therefore proposes an SBO methodology to overcome these challenges in the design of facility layouts, as explained in the following section. The methodology is explained by working through an industrial case study and is evaluated using the functional resonance analysis method (FRAM).

III. FACILITY LAYOUT DESIGN METHODOLOGY

Whereas there is no generic methodology in the literature based on SBO for FLD considering production and logistics systems, a clear understanding and mapping of the production and logistics processes involved in the layout can be crucial for the development of such projects. Accordingly the methodology outlined in Fig. 1 is proposed in this paper. Two versions of this methodology are presented. The first is oriented more to the management team and stakeholders, whereas the second focuses more on the engineering team and simulation experts.

A. FACILITY LAYOUT DESIGN METHODOLOGY: MANAGEMENT PERSPECTIVE

What follows is a detailed step-by-step methodology for managers and stakeholders, as well as for the engineering team supporting the FLD process with simulation and optimization.

Fig. 1 shows the five development stages in the boxes forming the horizontal arrow: **awareness**, **diagnosis**, **development**, **evaluation**, and **conclusion**. The two levels of implementation are presented in the vertical box on the left. These levels of implementation refer primarily to the level of analysis of the flows of products and materials occurring in the facility layout, as explained in the following paragraphs.

The **macro** implementation level is the strategic level, the big picture of flows, in terms of products per year and the movement of pallets of raw material, usually between buildings or facilities. By contrast, the **micro** implementation level is the more tactical-operational level, considering the detailed definition of the flows between departments and analyzing relevant families of products and variants and different kinds of materials and transport units. The order of implementation of the different activities is highly dependent on the facility being studied. However, experience gained from several industrial case studies suggests that the most common case is a top-down approach for the awareness, diagnosis, and development stages, and a bottom-up approach for the evaluation and conclusion stages. This division is explained by the required control and decision points of the management team in the first stages, and the required validation of the results and final decision in the last two stages.

In brief, the initial stage (**awareness**) includes defining the aim, scope, and objectives of the project, taking into account the strategy, vision, and ideal plan of the company. Thereafter a preliminary project plan and project team are defined. The outcome of this stage should be the key performance indicators to consider, a first analysis of what data will be needed during the project, and an indication of how the data should be collected. The second stage, **diagnosis**, aims to refine the definition of possible production and logistics constraints that can limit the design of the facility layout. It should also refine the project plan and data collection strategies. Here it is important to have a clear picture of the current and target states of the facility layout. The **development** stage, the main stage of the methodology, models the production and logistics systems related to the layout in order to analyze the system, finds possible weaknesses and bottlenecks, draws up what-if scenarios, and optimizes the production and logistic systems. The **evaluation** stage reviews the optimized production and logistic systems and evaluates a selection of FLDs to analyze their feasibility and optimize the best candidate solutions. The final stage, **conclusion**, summarizes the results of the optimization and final layout designs, letting managers and stakeholders choose from a set of optimized solutions.
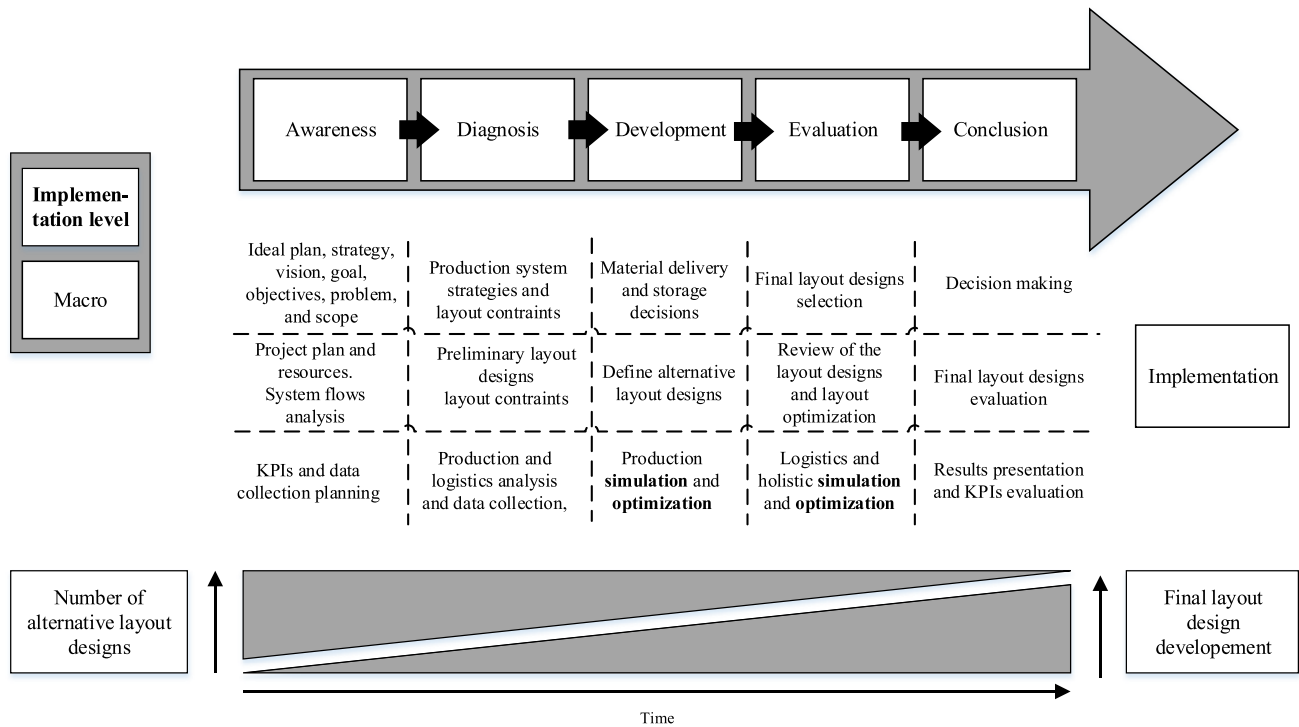
FIGURE 1. Holistic facility layout design methodology with simulation-based optimization, macro implementation level.

The micro implementation level of the methodology, more oriented to the engineering team and simulation experts, is presented in the following sub-section.

B. FACILITY LAYOUT DESIGN METHODOLOGY: ENGINEERING TEAM PERSPECTIVE

Fig. 2 presents the micro implementation level of the proposed methodology for FLD using SBO.

As before, the implementation order of the tasks represented in each column of the diagram depends on the implementation case. A logical structure going from the first element on the top of every column downwards is presented, but in some cases the order may vary. As the aim of this research is related to industrial implementations, an example explaining the different implementation stages will be provided. Some information on the layout and simulation models has been omitted due to confidentiality.

1) AWARENESS

The first stage of the implementation focuses on defining the aim and objectives of the FLD in relation to the vision, strategy, and ideal plan of the company. In the example case, the aim and objectives of the project were to design a new material handling system to suit a newly designed production system with four technologically adapted assembly lines, and propose a new facility layout to handle them. The key question was the importance of the location of the main supermarket (material preparation area) and its relevance to the material handling system.

The objectives were, therefore, to build and validate conceptual models and simulation models of the entire system for optimization. The vision and strategy of the company were an improved facility layout that could handle the implementation of new procedures and newly technologically adapted assembly lines. It should have an upgraded material handling system capable of handling diverse scenarios for future increased capacity of existing and new products. The ideal plan of the company was to have a flexible production system able to adapt to possible future changes in their production systems whereas using a relatively similar amount of resources and floor space to the current state.

The project team and the initial project plan needed to be defined at this stage. This group was appointed by the stakeholder of the project supported by the management team of the company. They selected a team of experienced technicians and engineers working in areas related to the project. The team included experience in production systems, logistics systems, facility layout, simulation, as well as a Lean expert. The next natural step was to define the preliminary project plan. For this task, an initial workshop was organized to review the aim and objectives of the project, as well as the vision, strategy, and ideal plan of the company. The Lean toolbox can be useful at this stage to establish a Lean working environment and to involve different levels of staff in the system to promote vertical integration and continuous improvement. The team accordingly organized Kaizen workshops for brainstorming and Gemba visits to the facility in question for all the project members of the preliminary
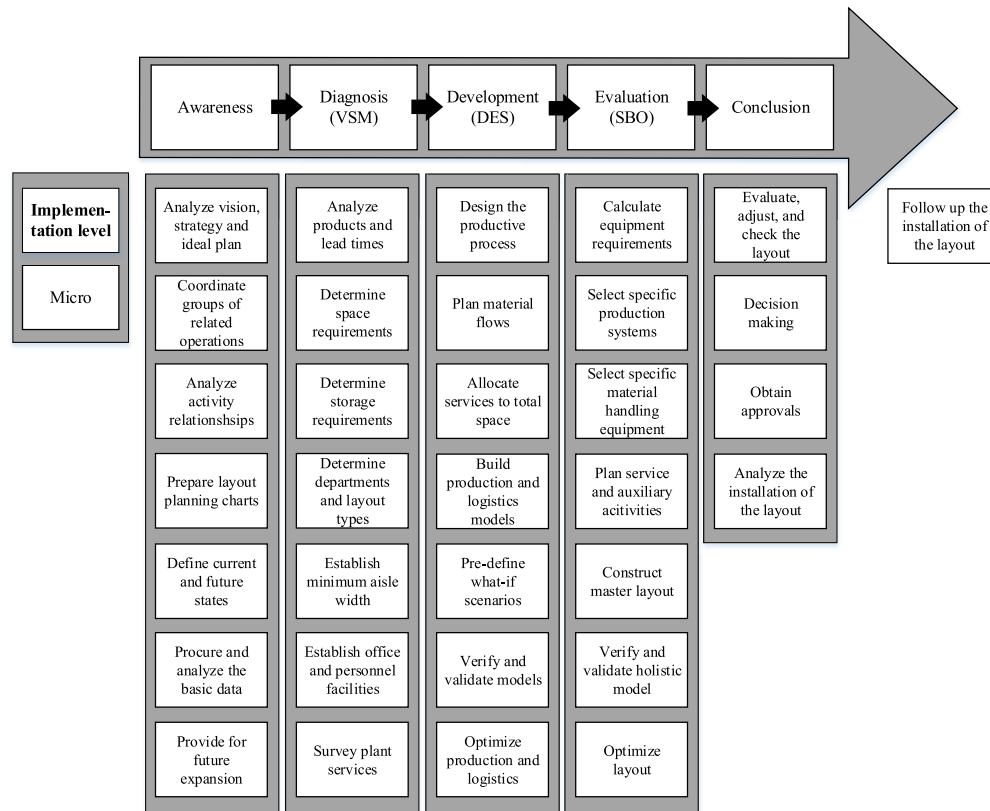
	Awareness	Diagnosis (VSM)	Development (DES)	Evaluation (SBO)	Conclusion
Implemen-tation level Micro	Analyze vision, strategy and ideal plan	Analyze products and lead times	Design the productive process	Calculate equipment requirements	Evaluate, adjust, and check the layout
	Coordinate groups of related operations	Determine space requirements	Plan material flows	Select specific production systems	Decision making
	Analyze activity relationships	Determine storage requirements	Allocate services to total space	Select specific material handling equipment	Obtain approvals
	Prepare layout planning charts	Determine departments and layout types	Build production and logistics models	Plan service and auxiliary activities	Analyze the installation of the layout
	Define current and future states	Establish minimum aisle width	Pre-define what-if scenarios	Construct master layout	
	Procure and analyze the basic data	Establish office and personnel facilities	Verify and validate models	Verify and validate holistic model	
	Provide for future expansion	Survey plant services	Optimize production and logistics	Optimize layout	

Follow up the installation of the layout

FIGURE 2. Holistic facility layout design methodology with simulation-based optimization, micro implementation level.

project team [29], [30]. With those terms clearly defined, the available resources were analyzed. The available time for the selected project team and the deadline for the solution of the project were analyzed. A deadline of nine months after this start of the project was set for the final designs.

Following the proposed methodology, another step at this awareness stage is to define the current state of the system. Thus existing blueprints of the current layout design were gathered. Value-stream mapping (VSM) identified the production and logistics processes related to this layout. A VSM is a representation of processes or activities that the products to be manufactured follow. It is important to try to have a holistic VSM of the entire current system in order to picture the expected solutions. Although a huge amount of data was missing at this stage, what data were available and could be collected were identified. This was a key step in order to adapt the project plan and allocate the necessary resources. Additionally, the planning for the target or future state followed the vision and ideal plan of the company, resulting in an upgraded holistic VSM of the future and ideal system. Some preliminary layouts were also designed.

At this first stage, it was also time to analyze possible constraints on the system and the layout, and the possible contribution of simulation and optimization to the project. Depending on the size and complexity of the project, traditional FLD methods or data sheets can be used if the sys-

tem and the amount of data are relatively trivial. Otherwise, simulation can be the proper tool [25]. Some constraints had to be defined here to facilitate the simulation process. These constraints related to the newly adapted assembly lines in all the solutions. The lines were required to remain in their current position, and be the same as for some other departments. Constraints were also imposed by the facility layout such as its shape, the available floor space, input and output locations, and flows of materials, products, and staff.

If there is some room to improve or redesign some of the production systems, this should be clearly identified at this stage in order to define the production system in the next stage. Once the project team was ready with a project plan, current and target state conceptual models, and constraints, it was time to proceed to the next stage, diagnosis.

2) DIAGNOSIS
At this second stage, the definition of the current systems and future alternative production systems should be clear. A key step is defining detailed, holistic VSMs of the facility layout. VSMs must represent all the relevant processes taking place in the facility. The nature of the production and logistics systems plays a vital role in defining the layout. The main layout types are fixed-position layout, functional layout, cell layout, and line or product layout [1]. Fixed-position layout is suitable for jobs with low volumes and variability of products.
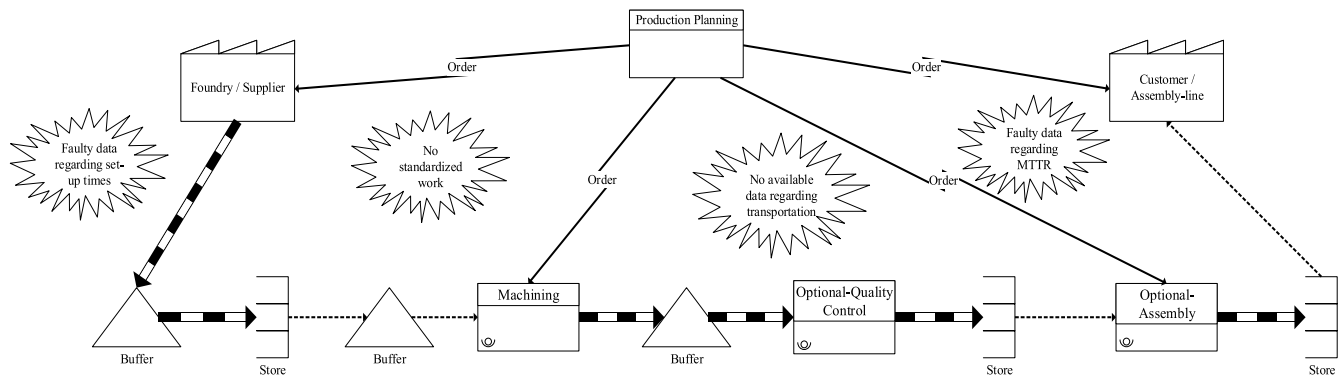
FIGURE 3. Holistic value-stream mapping defining relevant activities related to the facility layout.

It can be used for tailored production, repairs, or the manufacture of large products such as military aircraft or tanks, or in an engine workshop. A functional layout can be suitable for relatively low volumes of production and variants, as well as for jobbing and batch production. Cell layouts can be suitable for relatively large volumes of products and variants, as well as jobbing, batch production, and mass production. A product or line layout is usually implemented for large volumes of products and variants and continuous processing. If the flow can be individualized, it is possible to customize every product at different stations on the production line.

Some traditional methods of FLD, such as the graph-based method, can be used for the first draft of the revised facility layout. Using common sense and the information of experts, this layout design can be compared with the current one to define feasible alternatives that could satisfy the demands of the system. If necessary, simulation models can be used in the next stage to analyze the improvement of the existing production system as regards such issues as machining cells or areas, assembly lines, and changes in flows from suppliers. In that case, these systems should be included in the holistic VSM and the necessary data identified. The continuous involvement of managers and stakeholders, as well as subject matter experts and the project team, at these two first stages is key to the success of the project. If simulation has been identified as suitable for this project, the details should be firmed up at this stage. These include assigning the simulation team, determining the time needed for data collection, and translating the conceptual models or VSMs into the simulation language. The models should be verified and validated, and alternative layout scenarios should be defined. The modeling of the production systems is not strictly necessary if no changes are planned. However, all the information regarding the existing systems, such as throughput, lead time, work-in-progress, and material feeding approach, should be collected. The definition of the internal logistics systems has to be identified in the detailed VSM. The required transports and storage necessities should be identified, including product and material buffers located in the facility layout. The space required on corridors for transports, their paths, spaces to turn, loading and unloading areas, and charging and repair areas have to be identified. Suitable methods to transfer material and material handling options can be selected. A final reduced number of scenarios can be preselected to be evaluated using SBO. For example, scenarios can include retaining the existing material handling system, using manual forklifts, and possibly introducing an automated guided vehicle (AGV) system in the future.

It is important to survey the different areas and departments as well as plant services before continuing to the next stage. Items to be considered include the area, height, and location availability of the buildings, existing and possible input and output accesses, maintenance and emergency service accessibility, natural lighting, ventilation, and electrical and hydraulic fittings.

Summarizing all the information gathered at this stage provides a picture of the complexity, size, and scope of the project. The project plan and project team can then be reviewed and the decisions regarding simulation and DES can be double-checked. It is important to consider using a project management tool such as Microsoft Project to allocate enough time between tasks and to allocate proper resources [31]. The main output of this stage are the holistic VSMs of the current and possible future target states, an updated and refined project plan, the main constraints on the layout, and the current layout design with some alternative versions representing target and ideal stages. Fig. 3 is an example of a conceptual model of the system, including production and logistic aspects, including the processes taking place before and during assembly and their stores and buffers.

3) DEVELOPMENT
In this stage, a few alternative layout designs are reviewed together with the previously defined production solutions and VSMs. The internal logistics system should be modeled in this stage, using the combination of the alternative scenarios, the material and product flows, and safety and storage buffers. Some expertise or engineering background is usually necessary for the simulation task. The selection of the software tool should be made here. Some common software

tools used in the studied project were Flexsim, PlantSim, and Facts Analyzer [32]. The building of the simulation model can be guided by a simulation methodology such as Banks's or Law's simulation approaches [33], [34].

In this example, some assumptions had to be made to facilitate the modeling process. For example, the capacity and speed of the AGVs were set to a constant, and possible interruptions and routes were defined. Fig. 4 shows the simulation model for this example.
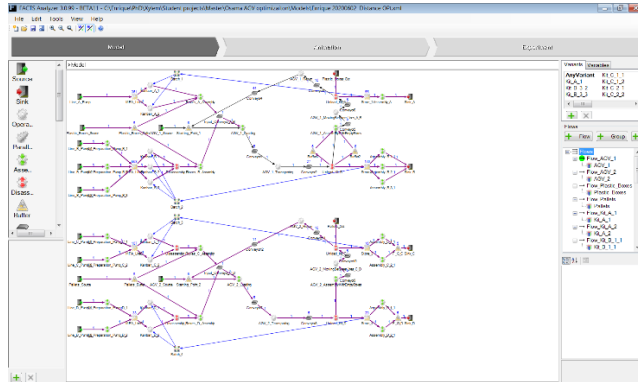

FIGURE 4. Discrete event simulation model of the production and logistics systems.

This simulation model represents the material preparation area, required buffers, assembly lines, and transport routes and transports. In this example, the capacity of every AGV was set to be one pallet and the speed 0.9 m/s. These values were selected based on the maximum load and capacity of current commercial AGVs.

At this stage, what-if scenarios can be defined, regarding possible configurations of the system, such as the kind of transports, their capacity, or rearrangements of the facility layout. The production systems (the assembly lines in this case) are modeled using a black-box approach as objects with inputs and outputs representing the throughput of the real assembly lines previously modeled.

The simulation model has to be verified and validated. Verification is to check that all the data and information have been properly translated into the simulation software. This can be done by double checking all the introduced data and going through the model step-by-step, checking with subject matter experts that no process or data are missing. The validation process ensures that the model represents the real system accurately, which can be done by comparing the output of the model with the data from the real system.

In this experiment, the validation process included the throughput for the different variants of products being produced in every one of the four assembly lines. These validated models allow for system analysis such as identifying bottlenecks, balance problems, and shape distributions on the facility layout [35]–[39]. When these problems become NP-hard, approximation methods approaches are recommended.

The simulation model or models obtained at this stage are the basis for the following stage.

4) EVALUATION

In the fourth stage of the methodology, the validated simulation models are analyzed. A reduced number of solutions for the production and logistics systems and suitable layout designs should be selected. Some what-if scenarios can be tested here, as well; for example, increasing throughput or changing the number of transports. However, when the number of possible scenarios or combinations of the system is significant and analysis becomes time-consuming, SBO is the proper tool for future work [40].

Common objectives in FLD include customer satisfaction, safety, security, and minimized length of flows, delays, work-in-progress, space required, and cost. Other objectives include clear flows of materials and persons, good staff conditions good communication and vertical integration, accessibility, long-term flexibility, and a good image [1]. An important step here is the location of the stores, supermarkets, or material preparation areas [41], [42]. A matrix of distances, a relationship chart, and a flow record chart are invaluable to provide a clear picture of the location and flows between the main departments [1]. The plant services and installations should be reviewed here to double-check that they do not affect the proposed production and logistics systems.

With some alternative layout designs on the table (e.g. those produced with the graph-based method), some suitable layout alternatives are translated into a holistic simulation model in which the production and logistics systems are represented in a simplified manner whereas keeping their input and output parameters. Modeling the production systems (such as machining areas, assembly, painting, and packing lines) as black boxes allows the simulation of the holistic system using common computers.

In the example, the number of AGVs required was considered as an optimization parameter, varying from one to five AGVs. The throughput of the production lines was established as a constraint that was kept constant at the maximum annual peak production. The number of AGVs and the distances between material preparation areas and assembly lines were optimization parameters to be minimized, but the locations of the assembly lines themselves were fixed. The work-in-progress and lead time were also optimization objectives to be minimized. The length, representing the capacity of the output conveyors of the material preparation area, and the input conveyors of the four assembly lines were also modeled as optimization objectives to be minimized.

The optimization algorithm selected was the non-dominated sorting genetic algorithm NSGA III [43] because it can cope with more than five conflicting objectives. The optimization uses simulated binary crossover and polynomial mutation as an optimization approach. It defines a set of variables and conflicting objectives to be achieved under a set of inequality and šequality constraints that must be satisfied
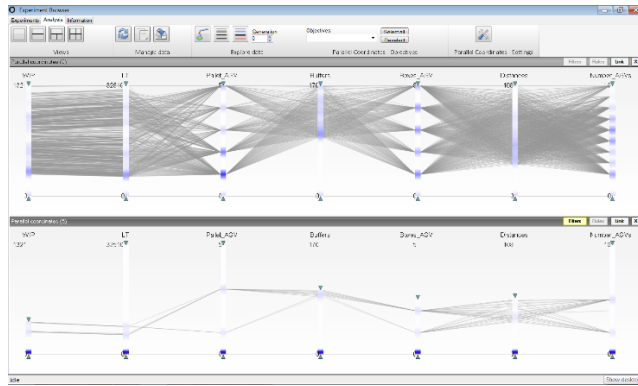
FIGURE 5. Results of optimizing the storage and buffer capacity, number of AGVs, routes, work-in-progress, and lead time.

within given upper and lower variable šbounds. The horizon of the simulation length was set to thirty days, considering the month with peaks of production, so that the system can handle the worst-case scenario. The warm-up period was determined to be two days to allow the model to function properly. Replication analysis was performed to define the number of replications required to minimize the variability of the simulation model. Ten replications of each run of the optimization were found to have sufficient accuracy for the purpose of this study. The expected solution was a trade-off between lead time, work-in-progress, distance between departments, buffer capacity, and number of transports.

The optimization results showed that the target state system was feasible. The results of the optimization yielded the minimum number of AGVs, routes, buffer capacities, and conveyor lengths required to keep suitable minimum values of throughput and lead time for the two main planned scenarios.

Some final layouts that can handle the production and logistics systems and constraints should be analyzed at this stage using SBO to find the locations of specific departments. The number of possible solutions increases considerably when designing a new facility layout from scratch, as there is no existing working facility layout from which to start. In those cases, an iterative process of diagnosis, development, and evaluation stages can be run until there are a reduced number of optimized layout alternatives.

5) CONCLUSION
In this stage of the methodology, a Kaizen workshop should be organized involving the entire project team, the persons responsible for the different areas, and managers and stakeholders so that they can review and validate the final layout alternatives. However, there is usually no straightforward solution. Often, it is a trade-off between conflicting objectives such as distances between areas or departments, lead time, number of AGVs, and buffer places. An example is presented in the Fig. 5. The optimized results can then be archived.

Fig. 5, a parallel-coordinates diagram, shows the results of the optimization, representing 5000 evaluations of possible configurations subject to the previously mentioned optimization objectives. The solutions with lower values of work-in-progress, lead time, distances, and number of transports are highlighted in the lower part of Fig. 5. Finally, it is up to stakeholders and managers to identify a set of feasible solutions limiting the boundaries of the conflicting objectives and considering available resources for implementation, and the vision, strategy, and ideal plan of the company. A key consideration at this stage can be the approximated cost of moving departments, machines, lines and transportation systems, or the cost of constructing facilities such as stores and buffers.

IV. METHODOLOGY EVALUATION
The proposed methodology was evaluated in several steps. First, its implementation was analyzed in two industrial case studies in two manufacturing company. The first case involved an FLD project with SBO at a medium-sized manufacturing company specialized in the production of electrical cabinets, giving precedence to operational performance, including factory floor space and production flow to meet increasing demand and product variety. Critical factors for achieving a desirable outcome were identified, and a new FLD was drawn up based on the optimization of these factors. The second case involved an FLD project including SBO at a large manufacturing company specialized in the production of water pumps. The objective was to increase quality while minimizing the cost of a layout redistribution on the main shop floor. In this case, an optimized layout was proposed considering the improved production and logistics systems. Both of the case studies showed that the method could be a suitable tool to guide the development of FLD projects when considering SBO. The main reasons are the clear division of tasks in chronological order, the development of the different stages of the methodology considering different types of resources for each one, and the positive impact of the definition of the project plan, project team, and data collection planning in the awareness and diagnosis stages. The guidelines for constructing the simulation model of the production and logistics system during the development stage and its combination with the final layout alternatives during the evaluation stage also show a clear advantage when establishing the steps to follow, the resources required, and the visualization of the expected results of implementation.

As part of the validation process, interviews were conducted with team members of these case studies. Additional interviews were conducted with layout engineers or responsible persons in similar manufacturing companies. In total ten interviews were held, focusing on the strengths and weaknesses of the proposed FLD methodology and its critical processes and variability. The interviewees mentioned a common lack of time, project planning, and resources. These defects could be remedied by dedicating more time to the planning activities in the awareness and diagnosis stages of this
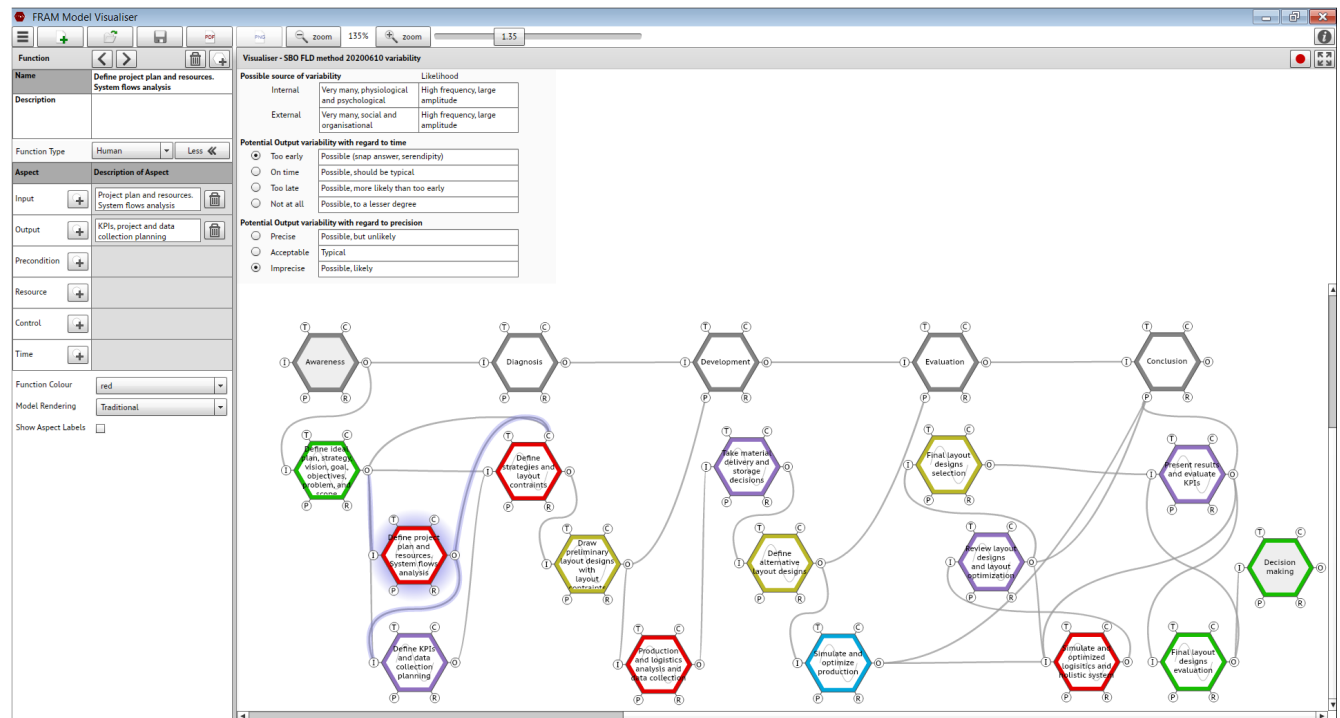
FIGURE 6. Visualization of the facility layout design methodology with simulation-based optimization in the functional resonance analysis method.

methodology. Another point highlighted was the general lack of expertise in simulation at the beginning of the project. Thus at least one team member should have simulation knowledge before starting this kind of FLD project.

These interviews were also used to identify the FRAM model critical activities in the methodology and their variability. FRAM is a methodology to represent and analyze the functioning of systems or procedures. It is usually used to analyze how a process or procedure is done, has been done, or will be done, capturing the essential features of the method, implying or embedding a generic model of the process or procedure for analysis [44].

In the FRAM model, the stages and processes of the FLD methodology are represented as activities, described as functions. These activities also identify the required connections and prerequisites of every step, evaluate a logical implementation order, and identify the most critical processes that limit the proper implementation of the FLD project. A visualization of the FRAM model is presented in Fig. 6.

Fig. 6 shows the different stages and processes of the FLD methodology presented in Fig. 1 together with their possible interconnections. The interconnections evaluate the order of implementation and feasibility of inputs and outputs of every object, as well as their preconditions and control aspects. Activities marked in different colors identify which activities are performed by managers or by the engineering team. Activities in blue are primarily performed by the simulation engineer or team. Activities in yellow are layout related and are carried out by the entire project team.

Critical activities were identified by introducing a classification of variability characteristics for every process for the origin of the information (the development of the research, observations, information from subject matter experts, and interviews). The classification criteria are based on the nature of the variability, whether technological, human, or organizational. Variability was graded as precise, acceptable, or imprecise, based on the accuracy of the outcome. The potential variability of every activity is represented in the FRAM model for its analysis and to determine its effect on other activities and the purpose of the model.

Evaluating the processes represented in the FRAM model using this classification highlights the variability of the processes of data collection, processes which require management involvement (green), and those related to layout selection (yellow). The variability of the processes seems to be high and the precision of the outcome low. Hence, more time and additional resources should be allocated to these activities when strict deadlines are considered in the design process of facility layouts, identifying the risk of delaying the project plan, or accepting infeasible results as part of this FLD methodology with SBO. These activities were in line with the activities identified in the mentioned interviews regarding lack of time, project planning, and simulation resources. Therefore the methodology was redesigned to highlight the importance of proper planning of these activities.

V. CONCLUSIONS AND FUTURE WORK
This paper analyzes the facility layout problem and common challenges when using SBO to analyze FLD. An SBO

methodology for FLD taking into account production and logistics constraints was proposed to overcome the challenges. Its application was explained by following an industrial case study and its evaluation performed with two industrial case studies and the FRAM method. The FLD methodology built into the FRAM model identified common weaknesses such as lack of time, project planning, resource allocation, data collection, and simulation expertise, highlighting the need to emphasize the planning stages (awareness and diagnosis). It is also important to follow the order of the different steps of the proposed FLD methodology.

Use of this methodology allowed a set of optimized layout designs to be presented to managers and stakeholders who could then choose from a high number of optimized solutions. The final trade-off solution had to be selected by management, weighing the importance of the key performance parameters such as lead time, work-in-progress, buffer capacities, routes, and the number of AGVs presented in the parallel-coordinates diagram. A key aspect of this FLD methodology was the involvement of managers and stakeholders during some specific stages of the process, integration of some Lean tools in the awareness and diagnosis stages, and DES and SBO in the development stage. The methodology thus facilitates the process of designing optimized FLD, taking into account the constraints on production and logistics systems.

The validation of this methodology by two industrial case studies, the FRAM model, and interviews with managers, stakeholders and layout engineering teams at several companies demonstrate that the methodology can serve as a support tool and a guideline for this kind of FLD project. Attention has been drawn to the importance of the proper definition of the project and project plan, the data collection approach, and the modeling approach, including several key performance indexes for optimizing the system. However, this evaluation could be extended to small-size companies and other domains outside manufacturing. This paper provides an example to managers, stakeholders, simulation engineering teams and FLD project teams of a good way to optimize layouts and facilitate the process of designing facility layouts able to handle considerable changes in the production setup of manufacturing companies.

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