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Constraint-Adaptive Layout Generation: A Flexible Framework to Integrate Real-World Constraints into Factory Planning

Dirk Rechkemmer[a,]*, Martin Benfer[a], Gisela Lanza[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe*

* Corresponding author. Tel.: +49 1523 9502634, *E-mail address:* dirk.rechkemmer@kit.edu

Abstract

The optimization of production layouts is becoming increasingly important as product diversity increases and corresponding planning becomes more dynamic. In the context of layout planning, companies must utilize available space optimally to maintain their competitive viability. To find the optimal solution and address numerous constraints, research is increasingly focusing on automated layout generation and optimization. However, in real-world applications, a multitude of constraints must be considered, which complicates the automated layout generation process. The type of parameters to be considered is highly flexible, allowing both hard and soft constraints, as well as dynamic constraints such as space requirements due to buffers or work positions, to arise from the optimization process. Existing approaches often address these aspects only partially or simplify them to such an extent that their practical applicability is limited. This paper proposes a constraint-adaptive framework that integrates diverse types of constraints into the layout optimization process. A categorization of relevant real-world constraints is developed and formalized in a model that supports a flexible and extensible representation of constraints. Different methods for representing boundary conditions are analyzed. The aim is to show how the constraints are considered in an optimization model, for example, as a graph model or as a penalty function. Consequently, an adaptive optimization mechanism is implemented, integrating classic metaheuristics with functions for handling dynamic constraints. To assess the efficacy of the proposed method, a case study is conducted in a brownfield scenario, considering the intricate spatial and regulatory constraints that characterize such contexts. The optimization results are evaluated in terms of layout quality and additional performance indicators derived from material flow simulations to validate the practical impact. The proposed approach contributes to a systematic methodology for incorporating realistic planning parameters into algorithmic layout generation, demonstrating its applicability under real industrial conditions.

Keywords: Material flow simulation; Optimization; Production Layout Planning; Factory Planning

1. Introduction

Planning production layouts is a fundamental lever for increasing operational efficiency and competitiveness [1]. In a market environment characterized by increasing product diversity, shorter life cycles, and volatile demand, flexible and highly optimized layouts are becoming increasingly important [2]. At the same time, a challenge lies in continuously updating simulation models with parameters and configurations to ensure they remain usable [3]. Companies face the challenge of maximizing the use of limited production space to reduce throughput times, minimize transport costs, and maintain high process stability. However, traditional, manual planning processes are time-consuming, subjective, and quickly reach their limits when it comes to the complexity of modern production systems, as they are hardly able to systematically capture and evaluate the multitude of interacting parameters and conflicting objectives.

For this reason, the automated generation and optimization of production layouts is increasingly becoming the focus of research [4], [5]. Algorithmic approaches promise to systematically explore the solution space and generate a large

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number of quantitatively evaluated layout alternatives in a short time. However, the practical application of these approaches in real industrial environments is associated with considerable hurdles. The reality of factory planning is characterized by a heterogeneous mix of hard, unchangeable restrictions such as building structures and safety regulations, soft, often contradictory goals such as minimum distances versus ergonomic workstations, and dynamic, layout-dependent requirements such as the space required for buffers resulting from transport times [6], [7]. The framework developed in this paper addresses this gap by proposing a methodology for realistic modeling and algorithmic processing of these complex requirements.

2. Related work

The state-of-the-art in automated layout planning offers a variety of optimization algorithms, primarily from the field of metaheuristics, such as genetic algorithms (GA), simulated annealing (SA), or particle swarm optimization (PSO). These approaches have proven their effectiveness in solving the quadratic assignment problem and its extensions, which often serve as mathematical abstractions of the layout problem. [8], [9], [10], [11], [12]

However, existing research often shows a significant gap between theory and industrial practice. Many models greatly simplify reality by treating machines as simple points or rectangles without functional zones for operation or maintenance. Most approaches focus on a limited number of constraints, typically collision avoidance and minimizing transport distance. At the same time, complex rules, such as floor load capacities, process zoning, or flexible personnel assignments, are rarely integrated. [13], [14], [15]

The most significant research gap is in the handling of dynamic, layout-dependent constraints [7], [15], [16], [17]. Requirements such as the space required for decoupling buffers are usually assumed to be fixed input variables. In reality, they are a direct function of transport times and process variances determined by the layout [18], [19]. This crucial feedback loop between layout geometry and process dynamics is mostly not covered. Additionally, there is a lack of higher-level, adaptive architectures that enable a planner to flexibly define their individual set of constraints and integrate them into the optimization process. There is a lack of a systematic methodology that formalizes the diversity of real constraints and translates them into a universally applicable, algorithmic solution approach.

3. Methodology

The deficits in previous research on automated layout generation and optimization of the various types of real -world constraints invite for further investigation. Therefore the following central research questions are derived:

Research question 1

How can the diverse and often contradictory boundary conditions of real factory planning (hard, soft, and dynamic requirements) be formalized in an integrated optimization model?

Research question 2

How must an architecture for layout optimization be designed so that it functions as a flexible, constraint-adaptive framework that universally adapts to different planning scenarios and enables the planner to configure specific requirements intuitively?

To answer these questions, research was conducted with industry partners to examine how production planners proceed with manual layout planning. These constraints were then used and implemented to a software-based optimization to create production layouts. A simple GA was introduced for the development of an automated solution in the later derived framework. Then the GA was expanded and tested with different types of constraints and target values.

4. Case Study

A use case from an industry partner was used to illustrate the topic with real-world examples. The task was to redesign a production line within a specified environment at a brownfield site. The study examined which real constraints are taken into account when planning production lines and in what order.

4.1. Formal modeling of production entities

To convert the physical reality of a brownfield production environment into a machine-readable and algorithmically processable format, a hierarchical, object-oriented model was developed. This approach now aims to consciously incorporate the complexity and structure of real boundary conditions. Only in this way can added value be delivered for real-world applications in industry. Instead, the functional complexity of each plant is mapped, which creates the basic prerequisite for applying nuanced and practice-relevant boundary conditions.

The core of this approach is the station object model (see Figure 1). Each production station, whether it is a CNC

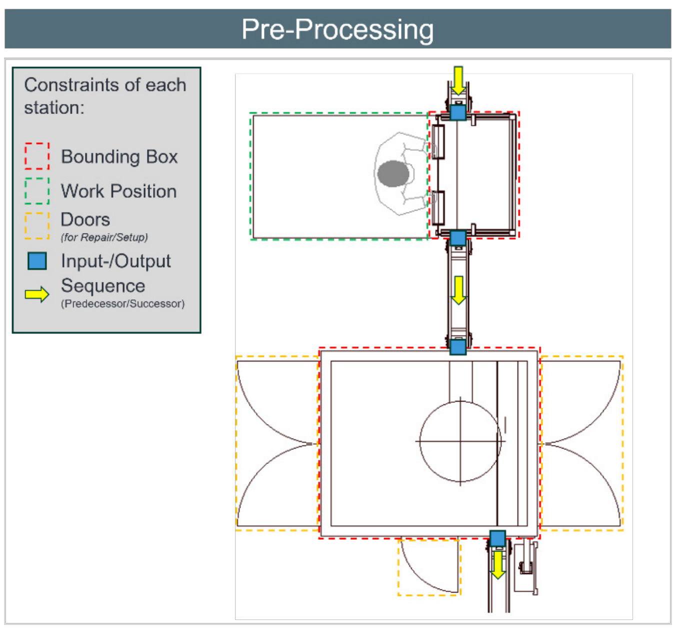

Figure 1 Pre-processing of station and layout data by detecting and defining bounding boxes and restricted zones

machine, a manual assembly workstation, or a testing booth, is defined as a composite object. This ensures that the various functional zones of a production line are linked together both logically and spatially. The central component of this model is the base geometry, which represents the unchangeable, physical footprint of the machine and serves as the primary element for collision detection. Several functionally defined zones are linked to this base geometry, which move with the base geometry when it is rotated or shifted.

One of the most important of these zones is the Oper*ator Zone*. It represents the area that must be kept clear for an operator to operate, load, or monitor the machine. The position of this zone relative to the machine, for example, at the front, is a fixed attribute of the model. This ensures that basic ergonomic requirements are met for every conceivable orientation of the station in the layout.

The *Material-Input and -Output-Zones* are crucial for mapping the logistical processes. These define the exact interfaces for the material flow. Depending on the application, they can be modeled as precise points for automated connection via conveyor technology or as handling areas for the provision of pallets, containers, or raw materials. These zones serve as start and end points for calculating all transport routes and costs in the subsequent optimization.

The *Maintenance Zone* models the temporary space required for maintenance and repair work, such as the swivel range of a control cabinet door. A key feature of this model is the linking of the zone to a frequency attribute (e.g., with each process/daily, weekly, or only for maintenance). This information enables the optimization algorithm to dynamically assess the importance of keeping this zone free and to make context-sensitive decisions.

The station model uses a range of non-geometric technical attributes. These include physical properties such as weight or energy requirements, process characteristics such as process type (machining/dirty or assembly/clean), and reliability parameters, including Mean Time To Repair, which are essential for the dynamic analysis of process stability and buffer requirements.

In addition to the station model, the production hall or part of it is formalized as an environment model. The hall is represented as a 2D polygon containing several specialized information layers. The first layer comprises static obstacles, such as unchangeable objects like building columns, load-bearing walls, or fixed main transport routes, which are modeled as absolute restricted areas. The second layer consists of zoned properties, whereby the hall area is divided into areas with specific properties. These can be zones with different floor load capacities, sections with special fire protection requirements, or defined cleanliness areas. The third level maps the positions of fixed utility sources, i.e., the connection points for media such as electricity, compressed air, or data networks. This detailed modeling of the station and its surroundings creates a detailed, digital representation of reality that serves as the basis for the subsequent, differentiated implementation of boundary conditions.

4.2. Implementation of hard constraints

Building on the detailed entity model, hard constraints are implemented as non-negotiable, binary rules that define the boundaries of the permissible solution space. The framework implements a multi-layered system of such rules to ensure the physical, technical, and regulatory correctness of each layout. The basic layer ensures geometric and spatial integrity (see Figure 2). It utilizes continuous geometric tests to prevent collisions between the base geometry and operator zone objects, as well as collisions with static obstacles, such as building columns or walls. Each object must also be located entirely within the hall boundaries. Another layer ensures technical and regulatory compliance by comparing the station attributes with the zone properties of the hall. This prevents, for example, a machine from exceeding the permissible floor load capacity of a location or equipment with a high fire risk from being placed outside the designated fire safety sections. It ensures that each operator zone is not only collision-free but also accessible from a main transport route. This can be verified using an A* pathfinding algorithm. Finally, a layer for hierarchical structures enables the mapping of fixed assemblies such as manufacturing islands, where the internal arrangement is unchangeable. The algorithm treats these as a single entity, allowing for the integration of proven partial solutions into the overall layout.

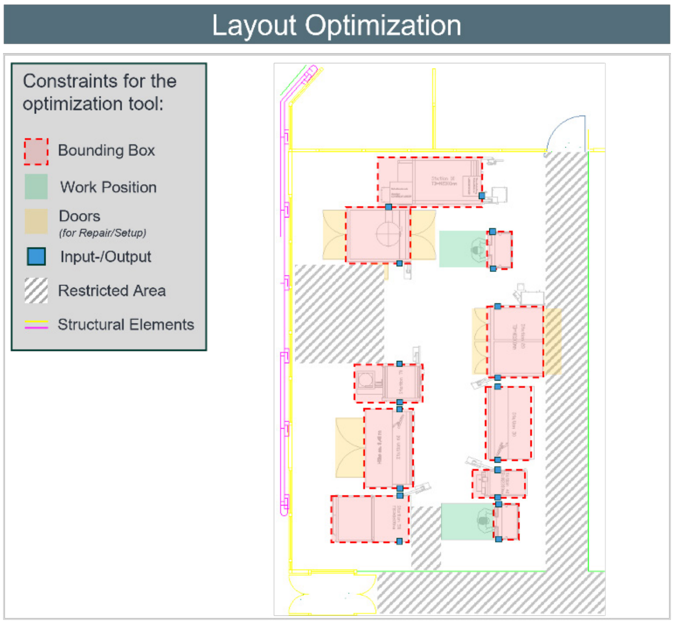

Figure 2 Layout optimization based on previously defined parameters, considering hard and soft constraints

4.3. Implementation of soft constraints

Soft constraints determine the quality of a layout by mapping planning objectives and preferences. The framework translates these into quantifiable penalty costs within a weighted fitness function. The primary goal is to optimize material and personnel flows. The cost function sums weighted path lengths for both material transport between stations and personnel walking distances between assigned workstations, resulting in an overall increase in efficiency.

An example of differentiated consideration is the context-sensitive handling of maintenance access which means that, for example, doors at processing stations can be used for maintenance, material delivery, or processing. Depending on the intended use, the upstream workstation must be permanently free and accessible, or it can also be located on a transport route, for example. Blocking the maintenance zone is not an exclusion criterion, but results in a penalty whose amount depends on the frequency of use. This means that infrequent access can be blocked in favor of a significant reduction in daily transport routes. Furthermore, process-driven zoning can be promoted by penalties for the proximity of incompatible process types (e.g., dirty vs. clean). This allows to group similar environmental conditions as organically process-homogeneous clusters. Additionally, secondary resource and infrastructure costs are minimized by penalizing long media supply lines and non-orthogonal machine alignment to reduce costs and improve visual order.

4.4. Implementation of dynamic constraints

The use case at the industrial partner has shown that it is often necessary to work with dynamic boundary conditions whose parameters emerge as emergent properties from the layout configuration. The case study therefore examined how these dynamic parameters can be integrated into the layout design process. A core example is adaptive buffer sizing, which addresses the connection between layout and process robustness. For each layout, transport times are calculated and combined with the stochastic process data of the stations (MTBF, MTTR, time variances). This is translated into a physical area that the algorithm must place as a new object in the layout. This feedback forces the user or later the algorithm to find a balanced compromise between geometric compactness and the buffer area required for process stability. Another dynamic aspect is the flexible allocation of personnel and the optimization of worker routes. In complex production systems, where a worker operates multiple machines, their routes become a layout-dependent optimization variable. Within the optimization the total distance for a worker's route between the operator zones of their assigned machines is calculated for each generated layout. These worker paths are integrated into the fitness function as a weighted cost factor in a multi-criteria optimization. This can lead to layouts in which machines are grouped according to operator responsibility, which potentially conflicts with pure material flow optimization and forces the algorithm to balance these two objectives. Strategic space reservation is used to account for future uncertainties. Areas can be defined as expansion zones. Placing objects in these zones is not prohibited but is subject to a high penalty fee. This protects strategically important areas from short-term use while allowing them to be utilized as an option in the event of bottlenecks, thereby integrating long-term strategic considerations into the optimization process.

5. Generalization

The case study showed that boundary conditions vary depending on requirements. In some cases, however, production planners want to deliberately test different scenarios and set boundary conditions or optimization variables. Therefore, it was investigated how dynamic boundary conditions can be implemented without requiring major changes. Its core task is to provide a robust optimization process that adapts flexibly to the problem defined by the planner, rather than requiring a new, specific implementation for each planning scenario. Figure 3 shows the general framework resulting from the findings from the case study. The adaptivity of the framework appears on the three conceptual levels of model, constraint, and process adaptivity:

- *Model adaptivity* is the ability to handle any modular production entities (stations, halls) by the user and their specific attributes
- *Constraint adaptivity* is the ability to process the three different classes of constraints simultaneously and orchestrate their respective logical implementation
- *Process adaptivity* is the design of the optimization process itself as a dynamic process that contains internal

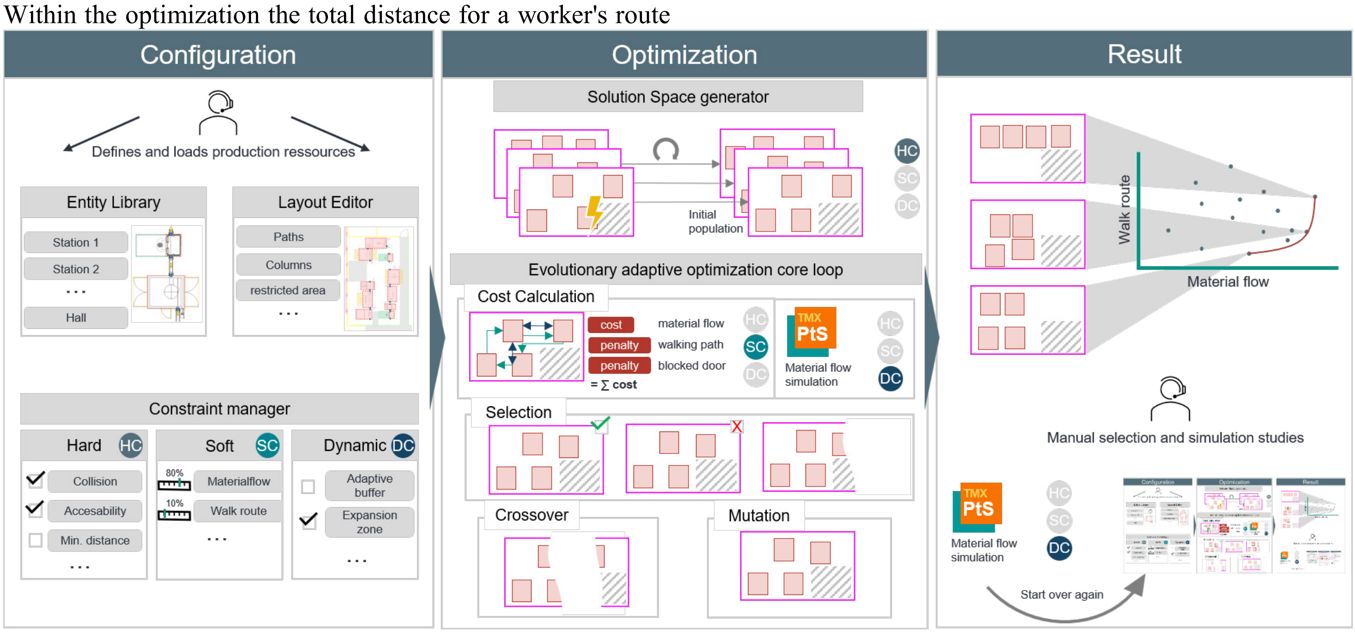

Figure 3 Framework for constraint-adaptive layout generation consisting of three columns

feedback loops based on the results of intermediate calculations

5.1. Architecture of the framework

The framework is based on a modular architecture that provides a clear separation between the problem definition and the core logic of the optimization algorithm, enabling adaptability.

The first module is the *configuration*, which serves as a flexible interface for the planner. Within this module, the specific entities of the planning problem are loaded from a library or redefined. It also includes a constraint manager, in which the planner "subscribes" to the boundary conditions relevant to its scenario from a predefined catalog. The planner activates the necessary hard constraints (e.g., collision checking), selects the soft constraints as optimization targets, and assigns them relative priority via weighting factors. Finally, they activate the required dynamic modules e.g., adaptive buffer calculation and configure their higher-level parameters.

The second module, the *solution space generator*, accepts this configuration and initializes the solution space. It generates an initial population of layouts that already satisfy all hard constraints using constraint-aware placement and repair heuristics. This ensures that the optimization process operates within the space of permissible solutions from the outset.

The third and central module is the *adaptive optimization core*, which implements a metaheuristic algorithm, typically a GA or SA. Adaptivity is achieved here through a multi-stage, orchestrated fitness evaluation. For each layout to be evaluated, the dynamic modules (e.g., buffer calculation) are executed first. It can also be decided to what extent the dynamic boundary conditions are evaluated. Afterwards, the costs of all activated soft constraints are calculated and aggregated with their respective weighting factors to form a final fitness value. The GA itself remains agnostic about the semantics of the constraints and only interacts with the standardized result of the fitness function. The optimization algorithm continues to iterate until a predefined termination criterion or preset value is reached. Ultimately, the user receives an overview of various configurations. The most promising layouts are displayed in more detail, and the user is given the option to view details and KPIs from the material flow simulation or make further adjustments. Depending on whether the material flow simulation was already integrated in the evolutionary loop, the user can further examine the final layouts in the simulation. The user can adjust and, for example, fix stations or start a new optimization run with customized buffer zones.

5.2. Technical implementation

The conceptual architecture is technically implemented as a layer-based software architecture with clearly defined interfaces, which guarantees the universality and expandability of the system. The core idea is to decouple the optimization core from the domain layer using the strategy design pattern. All boundary conditions are implemented individually as independent, interchangeable classes that fulfill a standard, predefined interface. For example, a class for collision conditions implements the method for validating the hard constraint interface (see Figure 1 and Figure 2), while a class for media supply cost implements a cost calculation method from the soft constraint interfaces, considering the weighting factor set by the user (see Figure 3). When a planner defines their problem in the configurator, a configuration object is created at runtime. This object contains not only the data of the entities to be placed, but also a list of instances of the constraint classes selected by the user. The fitness function of the optimization core receives this list and iterates over it. It calls the appropriate method for each object without having to know the specific logic of the individual constraint class. This architecture makes the framework universally applicable and expandable. To support a new constraint, a developer only needs to create a new class that implements the corresponding interface. The optimization core and the overall architecture remain unaffected. The new option can then be made available in the configurator for the planner. At the end the planner can select and compare the most promising layout variants (see Figure 4).

Figure 4 User Interface to display and compare two generated layouts

6. Discussion

The constraint-adaptive framework presented in this research demonstrates a methodological approach to bridging the gap between theoretical optimization models and the complex, multi-layered requirements of industrial factory planning. The case study conducted showed that the systematic categorization of constraints into hard, soft, and dynamic classes enables an effective representation of reality. In particular, the implementation of dynamic constraints, such as adaptive buffer sizing, represents a significant advance. It allows the generation of not only a geometrically optimized layout, but also a process-robust layout that remain stable despite fluctuations in machine failures and other process variables, by explicitly modeling the interdependency between spatial arrangement and process stability.

A central aspect of the discussion is the role of the human planner in interaction with the framework. The system is deliberately not designed as a "black box" that outputs a single, supposedly optimal solution. Instead, it acts as an intelligent tool that expands the planner's decision-making space. By configuring the soft constraints and their weighting factors, the planner formalizes their implicit priorities and strategic goals. The framework then systematically explores the solution space and presents a range of Pareto-optimal solutions that represent different compromises between competing goals (e.g., minimal transport costs vs. maximum flexibility). The final decision and qualitative evaluation thus remain with the expert, who can now apply their experience to a selection of highly optimized and valid alternatives.

A critical consideration is the potential additional effort required for modeling. The detailed recording of entities and constraints requires initial, careful data collection. However, this effort is justified by the high quality and robustness of the results, as well as the ability to quickly and cost-effectively run through a large number of scenarios. The technical implementation utilizing the strategy pattern has proven to be highly flexible and expandable, ensuring the framework's longevity and adaptability to future requirements.

7. Summary, and Outlook

This work proposes a constraint-adaptive framework for the automated optimization of production layouts, thereby closing the gap between theoretical models and industrial practice. The key to the framework's success lies in the systematic classification of real constraints into three classes, which enable its adaptive functionality. Hard constraints such as collision avoidance and technical conformity define the space of physically feasible solutions and guarantee their practical implementability. Soft constraints, such as transport routes and ergonomics, translate competing planning goals into a quantifiable, multi-criteria fitness function, enabling the algorithm to weigh complex trade-offs autonomously. The most significant innovation lies in the treatment of dynamic constraints, such as adaptive buffer dimensioning, which directly links the spatial arrangement to process robustness and ensures that layouts are efficient even under real, stochastic conditions. Through a modular software architecture based on the strategy pattern, the framework flexibly integrates these constraint types and decouples the generic optimization logic from the planner's specific problem definition. Instead of specifying a single solution, the system generates a portfolio of Pareto-optimal alternatives that serves as a sound and transparent basis for the planner's decision. Future research could focus on deepening the dynamic analysis by integrating additional layout-dependent factors and how to integrate material flow simulation without compromising in performance. Furthermore, machine learning can be used to enhance the system, enabling it to learn from historical data and proactively suggest promising configurations.

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