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Linguistic pattern-based facility layout optimization in designing sustainable manufacturing systems

Jerzy Grobelny and Rafał Michalski

Abstract—**Sustainable manufacturing plays a pivotal role in fostering economic growth, social development and environmental well-being. The Facility Layout Problem (FLP) in manufacturing involves optimizing the arrangement of resources for cost reduction and increased productivity. Sustainable facility layouts aim to minimize environmental impact, enhance social responsibility, and align with economic efficiency. Central considerations include resource efficiency, reduced energy consumption, and adherence to green building principles. Socially responsible layouts prioritize worker well-being, safety, and job satisfaction, contributing to a positive organizational reputation. The research introduces a novel method for solving FLP using scatter plots without predefined object locations. This approach employs optimization based on linguistic patterns with fuzzy variables, providing flexibility in modeling diverse manufacturing and supply chain problems. The paper presents simulation-based experiments to validate the proposed method, comparing it with a previous model. The generated scatter plots serve as tools for supporting sustainable manufacturing, offering qualitative and quantitative insights into designing systems that meet specific sustainability goals. The study contributes by bridging qualitative and quantitative approaches, particularly in handling imprecise and uncertain data. The proposed method's flexibility allows for formalizing and applying expert knowledge, influencing the continuous sustainability of manufacturing processes. Overall, the paper provides a comprehensive analysis of the proposed method, its sensitivity to parameter changes, and its potential impact on sustainable manufacturing.**

Index Terms— **Expert knowledge, Logistics, Scatter plots, Smart fuzzy optimization, Sustainability.**

I. INTRODUCTION

THE basic concept of sustainability is not new. In fact, our ancestors have employed it for generations by leveraging their knowledge of the environment and relationships between people and the natural world. Currently, the term is mostly associated with sustainable development defined in the Brundtland Report published by the United Nations [1], encompassing economic, social, and environmental development. These sustainability pillars were further specified in 2015 Sustainable Development Goals [2].

A. Sustainable Manufacturing

Manufacturing directly and indirectly influences all dimensions of sustainability and plays a pivotal role in several Sustainable Development Goals (SDGs). In Goal 8 (https://sdgs.un.org/goals/goal8), the emphasis is on promoting sustained, inclusive, and sustainable economic growth, along with creating full and productive employment opportunities and decent work for all. Goal 9 (https://sdgs.un.org/goals/goal9) highlights the importance of building resilient infrastructure, fostering inclusive and sustainable industrialization, and encouraging innovation, all of which are closely linked to manufacturing. Additionally, Goal 12 (https://sdgs.un.org/goals/goal12) seeks to ensure sustainable consumption and production patterns, recognizing that manufacturing practices significantly impact global consumption and sustainability goals. These interrelated SDGs underscore the critical role of the manufacturing sector in achieving a more sustainable and equitable future.

Given the relations between manufacturing and sustainability outlined above, it is not surprising that a considerable amount of scientific research has been devoted to sustainable manufacturing. Comprehensive systematic reviews on this topic were presented by Malek & Desai [3] and recently by Jamwal et al. [4], who focused on the last two decades of developments and trends. Other literature reviews were more specifically focused on the sustainable manufacturing concept within the context of Industry 4.0. Some of recent articles in this regard were published by Sartal et al. [5] and Tavares-Lehmann & Varum [6].

B. Facility Layout Problem (FLP)

Generally, FLP can be formally defined as the task of locating n objects within a given area or space based on a coefficient matrix describing the desired proximity between pairs of objects. The elements of the matrix, denoted by $l(r, t)$, represent the importance of the proximity between objects r and t. If the distance between them in the final configuration is symbolized as $d(r, t)$, the goal of designing a good layout is to minimize the sum of the products $l(r, t) \cdot d(r, t)$ over all pairs of objects.

Two main approaches exist in formulating this problem. The first assumes that the set of potential object locations is given, and the problem is to find the best assignment of objects to these positions. In this case, it is assumed that all objects have the same size and each object can be located in any available, earlier-specified place. The general model of this problem, called the quadratic assignment problem (QAP), was proposed by Koopmans and Beckmann as early as 1957 [7]. The NP-hard combinatorial complexity of QAP means that such problems

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are solved using various heuristic algorithms as extensively reviewed in recent works [8], [9], [10], [11].

The second approach to FLP assumes arbitrary sizes of objects and a freely defined area in which they should be located, not necessarily in a pre-established arrangement. This approach allows for greater flexibility in analyzed projects [12]. In this case, methods of generating solutions were proposed works such as [13], [14], [15], [16], [17] or [18], [19], [20], [21]. For convenience, the obtained solutions are usually presented visually, and their graphical representations resemble scatter plots. Unlike traditional optimization approaches, scatter plots are not the final, optimal solution for the layout problem. Instead, they provide a general suggestion regarding the spatial relationships between the components required to determine object placement.

Two dominant areas of application for layout problem solutions are production management, with focus on logistics systems (compare, for example [22], [23], [24], [25], [26]), and the interface design of interactive systems (see, for instance, [27], [28]). In the first sphere, layout design often focuses on minimizing production costs, especially transport costs. In the second area, the main goal is to maximize the quality or usability of interactive systems. In both application perspectives, the FLP model is usually extended beyond the formulated criterion of minimizing the sum of $l(r, t) \cdot d(r, t)$ with other significant criteria in these areas.

Concepts and measures of objects' closeness significance, that is $l(r, t)$, and distances can also be defined differently. For example, within the rapidly developing interactive systems, the $l(r, t)$ relationships defining connections between control elements can be represented by the distance between successive eye fixations, hand movements, finger or cursor movements. Some approaches take only frequency of use as a criterion, while others also consider the importance of interface elements and the order of their use. For instance, Bonney and Williams [29] proposed a multi-criteria and multi-stage heuristic-based model, in which objects' links $l(r, t)$ are defined by the designer using subjective rating scales.

C. Relations between Sustainable Manufacturing and FLP

The FLP is a critical issue in manufacturing and operations management, involving the determination of the optimal arrangement of machines, workstations, departments, and other resources within a manufacturing facility and between facility locations. The overarching goal is typically to minimize costs, enhance operational efficiency, and improve overall productivity. Manufacturing sustainability, as mentioned earlier, focuses on conducting manufacturing operations and external activities in an environmentally, socially, and economically responsible manner. The relationship between manufacturing sustainability and the FLP is multifaceted and significant.

Sustainable facility layout design encompasses several key considerations. It begins with the optimization of resource efficiency, where efficient layouts minimize material handling and transportation costs, thereby reducing energy consumption and resource waste. Furthermore, these layouts consider the environmental impact of manufacturing processes, striving to minimize material and product travel distances within the facility. This results in a reduction of emissions and waste generation, contributing to a decreased carbon footprint and overall environmental impact. Green building design principles are also integrated into the equation. Facility layout decisions align with green building standards by incorporating energy-efficient designs, renewable energy sources, and sustainable construction materials. This approach not only reduces energy consumption but also decreases greenhouse gas emissions.

In addition to environmental concerns, social responsibility is another core aspect. Optimized layouts promote fair labor practices and enhance the well-being of workers. They improve workstation ergonomics and ensure safe working conditions, ultimately reducing workplace injuries and fostering higher employee morale. Appropriate layouts minimize unnecessary worker movements and manual material handling operations, thereby improving work quality and employee satisfaction. This positively influences the organization's overall reputation and its relationships with workers and communities.

In summary, there are significant relationships between manufacturing sustainability and the facility layout problem. Sustainable facility layouts consider environmental, social, and economic aspects to optimize resource use, reduce environmental impact, enhance safety, and align with sustainability goals. By integrating sustainability principles into facility layout decisions, manufacturers can improve their overall sustainability performance, reducing their environmental footprint and contributing to more responsible and efficient manufacturing and logistic processes.

II. RESEARCH GOALS AND CONTRIBUTION

As the analysis of 541 scientific articles showed, more than 70 % of research on sustainable manufacturing is primarily directed to qualitative features [3]. Therefore, there is an increasing need to extend the body of literature with studies focused on more quantitative approaches. Among them, methodologies taking advantage of imprecise and uncertain data should be of particular interest. They allow for modeling and applying expert knowledge in a formal and systematic way, classifying somewhere in between qualitative and quantitative approaches. On the one hand, they grasp qualitative imprecise expert statements, and on the other hand, they allow representing such knowledge mathematically in a way that makes quantitative optimization feasible.

In this paper, optimization and decision-making are based on the concept of linguistic patterns involving a fuzzy background. They are used not only to define relationships within the manufacturing system but also to constitute the foundation of the assessment criteria. As the approach is highly flexible, it allows for modelling a vast variety of real manufacturing and supply chain problems. Such a methodology facilitates formalizing, storing, applying and systematically improving expert knowledge about internal and external logistic processes. This, in turn, may have a significant impact on the continuous sustainability of manufacturing.

The main contributions of this work are:

- Proposal of a novel method for solving facility layout problem represented by scatter plots on a plane without predefined object locations. The approach uses smart optimization based on linguistic patterns involving a fuzzy definition of variables. The basis for obtaining these plots in the present study is the concept of wandering agents introduced in [30]. In particular, we have extended the model from the cited work by including additional criteria in the form of specially created patterns, which considerably change the behavior of agents compared to the previous model.
- A thorough examination of the novel approach by designing, performing and analyzing a series of simulation experiments. These studies include artificial problems of various sizes with a variety of randomly generated relationships, designs with known optimal structures, and two real-life examples. The results of the simulations for randomly generated relationships can be used as recommendations for specifying parameters for real-life problems of similar characteristics.
- Similar, simulation-based analysis of our previous method from [30] aimed at determining the sensitivity of that approach to changes in parameter definitions. Such research allowed for the extensive comparative analysis of the previous model with the present paper proposal.
- The application of R square measure for comparisons of our LP-based approaches with other FLP methods generating scatter plots. The R^2 is calculated for the linear regression relating reconstructed relationships with object pair distances.
- Demonstration and discussion of how the generated scatter plot solutions to the FLP can be used as a tool for supporting sustainable manufacturing.
- Provision of qualitative and quantitative data on which types of scatter plots generated according to two version of linguistics pattern-based optimization criteria are suitable for designing manufacturing systems that meet specific sustainability goals.

In the next section, we briefly describe the proposed idea including terms and definitions from our previous method that are necessary to understand how the current approach behaves.

III. LINGUISTIC PATTERNS FOR FLP SCATTERED PLOTS

The method proposed in this study is inspired by our approach detailed in [30], which involves placing a group of agents randomly within a rectangular area, and simulating their movements based on linguistic patterns (LP). These patterns represent the logical phrases describing the desired state of relationships between each pair of agents in a system. The goal of this dynamic process is to gradually improve the extent to which the whole layout fulfills these patterns. The ultimate result of agent wandering is a scatter plot, which arises when all patterns are satisfied or when there is an equilibrium of virtual forces generated based on these patterns. Since each agent in the further analyzed examples represents an element of the production or logistics system, these terms are used interchangeably. The basic LP (1) defines the target relationship for each pair of components as follows:

***Pattern_1 (P1)*:** **If** RELATIONSHIP_BETWEEN (*r, t*) is POSITIVE **Then** (*r*) is in SMALL_DISTANCE from (*t*) (1)

In this paper, we specify the truth of the RELATIONSHIP_BETWEEN(*r, t*) is POSITIVE expression as the division of RELATIONSHIP_BETWEEN(*r, t*) by the maximal value of all RELATIONSHIP_BETWEEN(*r, t*). The formula is graphically illustrated in Fig. 1(a). In turn, Fig. 1(b) demonstrates the fuzzy set definition of the SMALL_DISTANCE expression.

In our approach, *P2* specified below (2), is responsible for creating repulsive forces between components that allow for forming neutral zones around elements. The truth values for this pattern is demonstrated in Fig. 1(c).

Pattern_2 (P2): DISTANCE_BETWEEN (*r*, *t*) is larger than NEUTRAL_ZONE (2)

The overall layout components' well-being is evaluated by these two patterns. To calculate implication truths for *P1*, one can take advantage of the Łukasiewicz formula [18], [27], [31], that is:

$$\text{Truth}(\boldsymbol{P1}) = \text{minimum}\{1, 1 - \text{Truth}(LeftImpl) + \text{Truth}(RightImpl)\}, \tag{3}$$

where Truth(*LeftImpl*) and Truth(*RightImpl*) denote the truth degrees of the left and right side of the implication. If the relationship between *Object_1* and *Object_2* according to equation (3) is smaller than 1, *Object_1* would try to increase the truth by moving incrementally towards *Object_2*. The speed of this movement is greater the higher the value of the expression {1 – Truth(*P1*)} is. This expression defines the vector magnitude of the attracting virtual force between two objects and is denoted as *VF*(*Object_1*, *Object_2*). The $\overrightarrow{VF}$ vector lies on the line connecting *Object_1* and *Object_2*. The object displacement in the force of attraction direction in one step of the algorithm consists in making a movement proportional to the *VF* value. The specific length of this step is determined by parameter *s*, which is expressed as a percentage of the length of the maximum side of the plane.

Similar computations are performed for *P2*. The truth value in this case is zero if the pair crosses the NEUTRAL_ZONE and is equal to one otherwise. Therefore, the truth for *P2* (2) creates a repulsive force of value 1 or generates no force at all. The average of truth values calculated for *P1* and *P2* over all pairs of objects is an indicator of the quality of the obtained scatter plot. The detailed description of this stepwise procedure is given in [30].

In the research presented here, we have expanded the proposed approach with an additional criterion specified in a form of a linguistic pattern. It is easy to see that *P1* generates virtual forces only for objects that are related to each other. Therefore, the entire optimization process is focused on them, while the not-linked objects do not have any influence on the final solution except for maintaining neutral zones defined in *P2*. In many real-world problems, ignoring objects can result in overall or local excessive density of the layout design. This may adversely affect the functioning of the system despite optimally

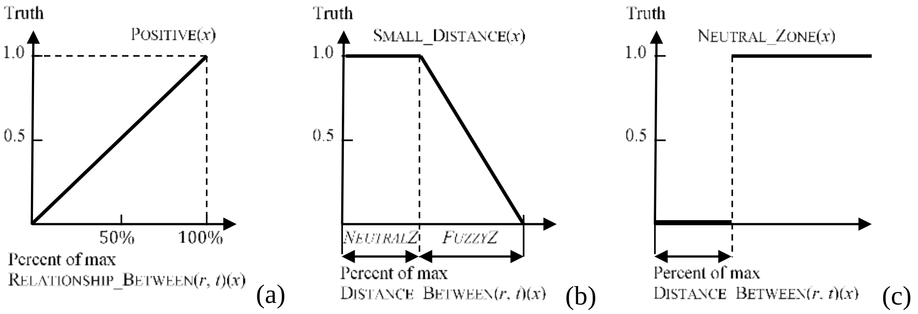

Fig. 1. Graphical definitions of truth values for pattern expressions (a) POSITIVE, (b) SMALL_DISTANCE, and (c) NEUTRAL_ZONE.

fulfilling *P1* and *P2*. Therefore, a natural complement to these patterns seems to be the introduction of a requirement that if objects (*r*, *t*) are close to each other, then their relationship is POSITIVE. Formally, the formula for this pattern is analogous to *P1* and uses the same parameter definitions, that is:

Pattern_3 (P3)**:** **If** (*r*) is in SMALL_DISTANCE from (*t*) **Then** RELATIONSHIP_BETWEEN(*r*, *t*) is POSITIVE (4)

If we want to evaluate the truth of a given scatter plot based on the conjunction of *P1* & *P3*, the calculation for each pair of agents will proceed as follows:

$$\begin{aligned}&\text{Truth}(\boldsymbol{P1}\ \text{AND}\ \boldsymbol{P3}) = \\ &\text{minimum}\ \{ \\ &\quad \text{minimum}[1,\ 1 - \text{Truth}(\mathit{LeftImpl}) + \text{Truth}(\mathit{RightImpl})], \\ &\quad \text{minimum}[1,\ 1 - \text{Truth}(\mathit{RightImpl}) + \text{Truth}(\mathit{LeftImpl})] \\ &\}. \end{aligned} \tag{5}$$

Analogous to *P1*, the truth deficit for *P3* generates a virtual force between the considered pair of objects. However, bridging this deficit requires moving away agents with low levels of relationship values (POSITIVE) lying close to each other. It can be noticed that Truth(*P1* AND *P3*) can be replaced by the logical expression *IF AND ONLY IF* (IFF). Thus, we have:

$$\begin{aligned}&\text{Truth}(\boldsymbol{P1}\ \text{AND}\ \boldsymbol{P3}) = \\ &\text{Truth}[\textbf{IFF}\ \text{RELATIONSHIP\_BETWEEN}\ (r, t)\ \text{is POSITIVE} \\ &\quad \textbf{Then}\ (r)\ \text{is in SMALL\_DISTANCE FROM}\ (t)]. \end{aligned} \tag{6}$$

In our computer implementation of the model, layout components are graphically represented as numbered crosses or squares of any size. The analysis area is defined as a rectangle of any size in any units, and distances within the area are determined as parts of the longer side length of the area. In the case of designing a production, logistics or information system, the arranged elements can be easily imagined and represented as objects in our model. POSITIVE attitude in this context simply refers to the relation in which system components are functionally related or occur in sequences of analyzed processes. Distances can be identified, for example, with the physical size of each element. For more details refer to [30]. The ability to use expressions similar to natural language allows for flexible application of LP to optimization tasks that utilize imprecise knowledge, such as subjective expert opinions on the designed factory layout.

In the experiments presented in the following sections of this paper, we focused on comparative studies of moving object behavior and characteristics of resulting scatter plots for two approaches to specifying optimization process criteria, that is, Truth(*P1*) and Truth(*P1* & *P3*). In our computer implementation, we use respective average truths calculated across all pairs of objects to assess the specific scatter plot solution to FLP.

In the following section, we investigate the influence of parameters on the behavior of the proposed approach. The shape of the path of each wandering object in our method, as well as the final structure of the obtained scatter plot, depends strongly on the definition of distance and step size. Therefore, we designed experiments aimed at identifying the relationship between the quality of scatter plot solutions and those variables for a variety of layout optimization tasks differing in sizes (*small*, *medium*, *big*) and relationship densities (*small*, *medium*, *big*).

IV. SIMULATION EXPERIMENTS

The section includes three series of simulation experiments aimed at assessing the sensitivity of our proposal to basic parameter and linguistic pattern changes. First, we focus on artificial examples of various sizes, including random relationships with the specified density, to check how our approach behaves in qualitatively different scenarios. Next, we examine a sample layout with a known structure that involves random relationships between objects. Finally, we experimentally examine two real-life problems related to production system and control panel designs.

A. Layouts with Random Relationships of Specified Density

1. Experimental Design and Procedure

In this section, we study *small*, *medium*, and *big* problems containing 16 (4×4), 36 (6×6), and 64 (8×8) objects respectively. For these sets of items, we generated three random relationship densities, that is 5%, 10%, and 15%. In general, we examined nine different types of configurations (3 problem sizes {4×4, 6×6, 8×8}) × (3 relationship densities {5%, 10%, 15%}). A simulation study was performed for each layout type, involving two factors: fuzzy distance membership function type (FD), representing the SMALL_DISTANCE linguistic variable from Fig. 1(b) and virtual force strength (VF).

For comparative purposes, we employed both the current paper's algorithm proposal and our previous approach

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published in [30]. The number of trials for each layout type, specific experimental condition, and optimization method amounted to 30, which is considered to be the minimal threshold required to apply statistical tests to the obtained results. The number of a single simulation steps was set at 200, which resulted from initial runs observation that object positions stabilized after this number of steps.

For all layout types, we initially defined five variants of FD and five levels of VF: VF1 = 1%, VF2 = 2%, VF3 = 3%, VF4 = 4%, VF5 = 5%. The percentages refer to the width of the layout plane and are referred to as *Percent of max* DISTANCE_BETWEEN(*r*, *t*)(*x*) in Fig. 1. Fuzzy membership functions for FD used in these experiments were defined as linear decreasing functions beginning after value NEUTRALZ in the following way: FD05: MF(1%) = 1 to MF(5%) = 0, FD10: MF(1%) = 1 to MF(10%) = 0, FD15: MF(1%) = 1 to MF(15%) = 0, FD20: MF(1%) = 1 to MF(20%) = 0, FD25: MF(1%) = 1 to MF(25%) = 0, where the universe of discourse was specified between 0% and 100%.

In a series of pilot simulations, we first determined reasonable ranges of basic parameters, such as distance definitions and virtual step boundaries. This ensured scatter plot objects' integrity and that all objects stayed within the design plane. For a detailed procedure, compare the information presented in Fig. A.5 in the supplementary material. After conducting initial analyses of objects' behavior dynamics, we set the NEUTRALZ value from Fig. 1(b) at 1% in all FD membership function definitions.

In all experimental conditions, the fuzzy membership function for the relationship linguistic variable POSITIVE from Fig. 1(a) was defined linearly, from MF($x = 0\%$) = 0 to MF($x = 100\%$) = 1, which is shown in Fig. 1(a). The universe of discourse was specified between 0% and 100%. In the situation where the specific combination of these two factors' levels resulted in moving objects outside the defined plane boundaries, the simulation results were not included. All the obtained results were analyzed by two-way Analysis of variance (ANOVA) followed by a series of post-hoc tests to verify if the differences between factor levels are statistically meaningful.

2. Results

Outcomes for all types of random relationship densities are comprehensively put together in Figs. 6, 8, and 10 of the supplementary material. The post-hoc test results for both main factors are also included in supplementary material in TABLES A.I – A.XVIII.

As far as layouts with 36 objects are concerned, all examined effects along with their interactions statistically significantly ($p < 0.05$) influenced both dependent variables, that is Truth(*Pattern1*) for our previous algorithm [30], and Truth(*P1* & *P2*) for the current study proposal. There is only one exception for the layout with a relationship density of 15%, where the *Virtual Force* factor did not significantly ($p = 0.11$) differentiate mean Truth values for (*P1* & *P3*).

Exemplary ANOVA statistics, probabilities along with mean truth values, obtained for the medium-size problems consisting of 36 objects with 10% relationship density are given in Fig. 2. The presented graphs of mean truth values suggest clear patterns of the examined algorithms' behavior depending on the analyzed factors. As far as the virtual force effect is concerned, its impact on Truth(*P1*) is clearly linearly decreasing, which means that bigger virtual force values provide worse results while applying our first algorithm.

A somewhat different pattern can be observed for the present article algorithm. In the layouts with 5% and 10% density of random relationships, bigger values of virtual force at first improve the average Truth(*P1* & *P3*). However, further increase of the virtual force improves the goal function to a much lesser degree. This phenomenon is visible in the LSD post-hoc tests showing no statistically meaningful difference between VF3 and VF4 ($p = 0.336$) for layouts with 5% density of relationships, VF3 vs. VF4 ($p = 0.103$), and VF4 vs. VF5 ($p = 0.781$) in layouts with 10% relationship density (see TABLES A.VII and A.IX in the supplementary material).

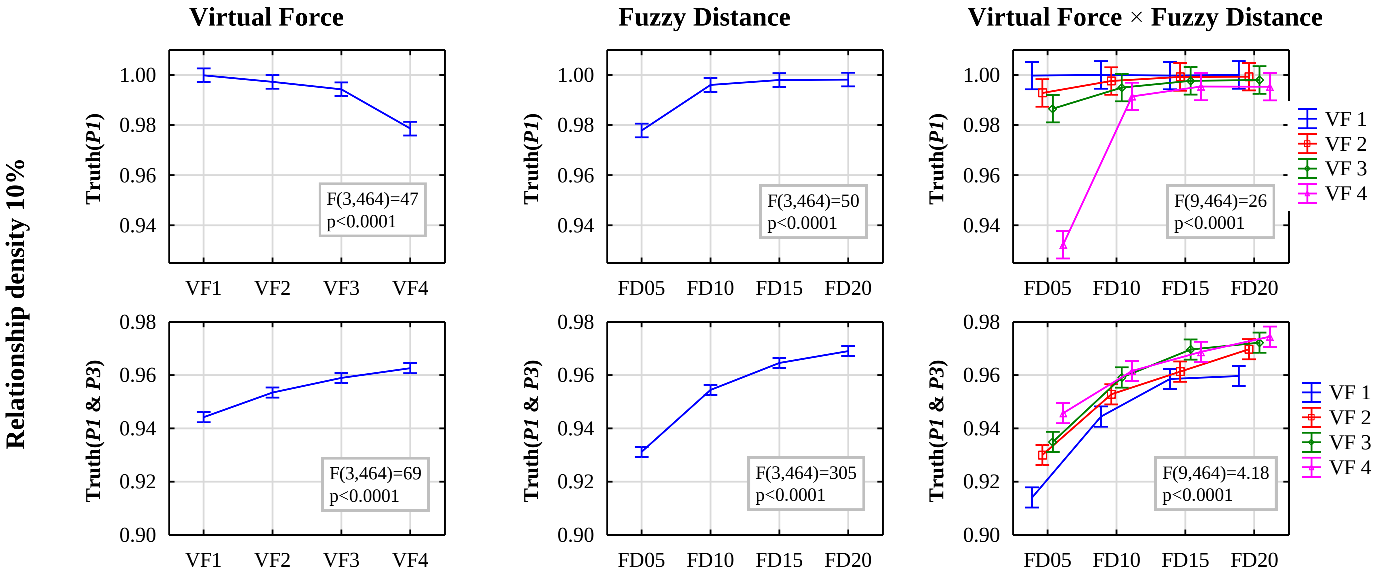

Fig. 2. ANOVAS for 6×6 layouts with 10% random densities. Vertical bars denote 0.95 confidence intervals

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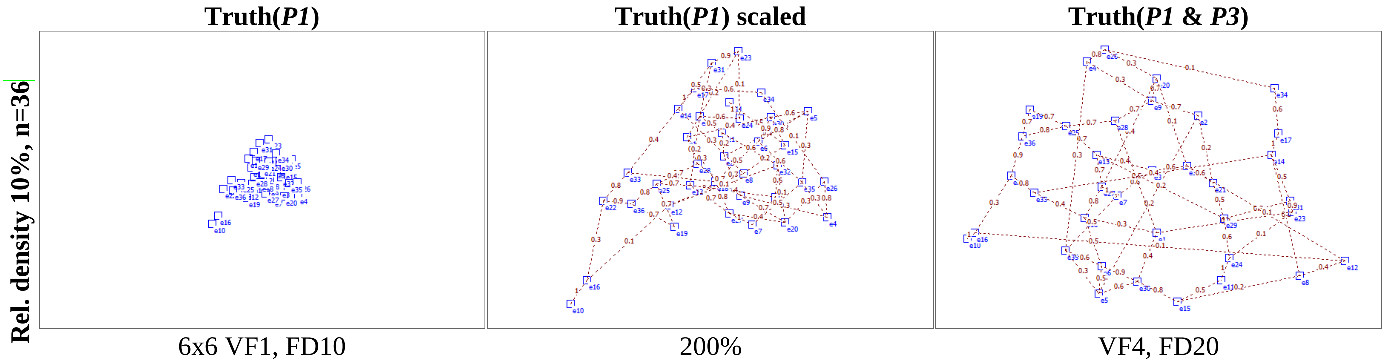

6x6 VF1, FD10 200% VF4, FD20

Fig. 3. Sample best layouts with random relationship densities.

The fuzzy distance factor had a qualitatively similar influence for both examined algorithms across all investigated object relationship densities. The longer the FuzzyZ section of the Small_Distance variable was, the higher truth values were for both *P1* and (*P1* & *P3*). However, one should bear in mind that increasing the FuzzyZ section beyond maximal values presented in Fig. 2 will move the objects outside the defined plane, resulting in unacceptable solutions.

Also, the general pattern for consecutive levels of the *Fuzzy Distance* factor was almost identical in all simulations. The change from initial FD05 to FD10 considerably improved mean truth values. Further increasing the FuzzyZ section had a smaller and smaller positive effect on dependent variables. In some cases, the differences were even statistically irrelevant; for example, the difference between FD10 and FD15 for Truth(*P1* & *P3*) in layouts with 5% and 10% relationship densities was insignificant with $p = 0.305$ and $p = 0.176$, respectively (TABLE A.VIII and A.X of the supplementary material).

Significant interactions between *Virtual Force* and *Fuzzy Distance* indicate that both factors influence the truth values, and they should not be set independently. One may also notice that the maximal FuzzyZ section of the Small_Distance linguistic variable that did not cause the objects to move outside the available area does not exceed 20%. For layouts with a 5% relationship density was even smaller and amounted to 15%.

The simulation outcomes for *small* (16) and *big* (64) layouts exhibit similar patterns. Anova findings and mean truth values for them are provided in the supplementary material in Figs. A.8 and A.10, respectively. The corresponding LSD post-hoc test outcomes are put together in TABLES A.I, A.VI, and A.XIII, A.XVIII.

Sample best solutions are illustrated in Fig. 3, while a full set of the best solutions obtained in all simulation experiments are presented in Figs. A.7, A.9, A.11 in the supplementary material. In all these scatter plots, there is an apparent distinction between solutions for both examined algorithms. Solutions for Truth(*P1*) are considerably more compact then those for the present study approach (Truth(*P1* & *P3*)). Scaled-up versions of solutions for Truth(*P1*) allow comparing examined structures qualitatively. Although in both approaches strongly associated objects tend to be positioned close to each other, the major difference was concerned with the lack of dispersing force component. Because of that, even the zoomed version of the algorithm based on Truth(*P1*) is more cluttered than the new proposal. One can also notice that investigated parameter combinations that produced the best results differed considerably for these two types of scatter plot generation procedures across all type of simulation experiments.

B. Layouts with Known Structures

The second series of experimental simulations comprised an artificially generated layout with a known structure. Fig. 4(a) shows this configuration for 36 objects with randomly generated truth values of Positive relationships.

1. Experimental Design and Procedure

Similarly as in the previous series of experiments, we generated scatter plots according to our two methods. In the first one [30], the average truth value satisfying *P1* was treated as the dependent variable, whereas in the second one, the dependent variable corresponded to the present study proposal and included *P1* & *P3*.

As previously, we investigated two independent variables FD (Small_Distance) and VF with the same five levels of those factors and identical definition of the Positive variable. We ran the simulations 30 times for each experimental condition and optimization method. A two-way analysis of variance along with post-hoc tests was employed to examine the outcomes. When in any experimental condition the resulting configuration included objects outside the defined plane, the results were not further investigated.

2. Results

Mean truths regarding the known structure of 36 objects for all experimental conditions along with corresponding ANOVA statistics and probabilities are presented in Fig. A.12 in the supplementary material. The relationship density for this example was approximately equal 5%, thus it is not surprising that the results pattern resembles the version of completely randomly generated 36 items layouts with similar relationship density given in Fig. A.8. Also here, both investigated factors and their interactions statistically significantly differentiated mean truth values with $p < 0.0001$ in each case. However, some minor differences were noticed for post-hoc tests. In this example, Mean Truth(*P1* & *P3*) values were insignificant already for *Virtual Force* bigger than 2% (TABLE A.XIX in

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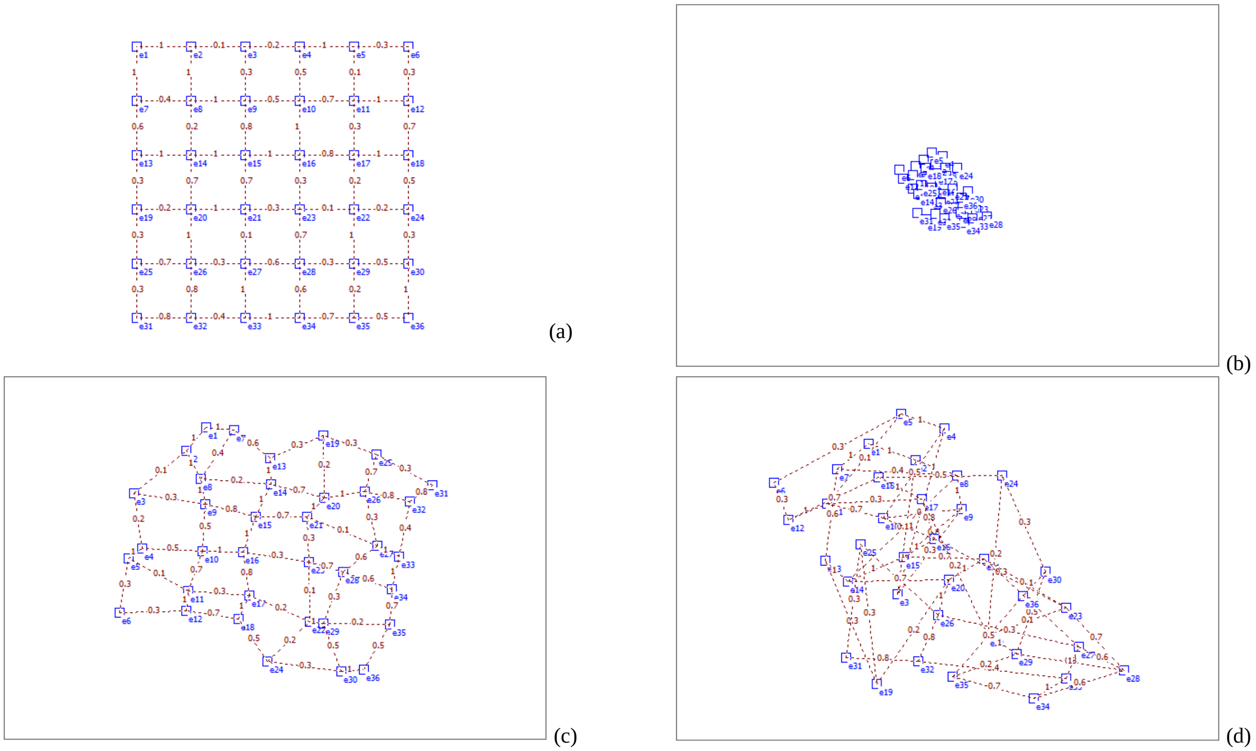

Fig. 4. Artificially created sample layout comprising a known structure of 36 objects with randomly generated truth values of POSITIVE relationships (a); the best solution for *P1* (b) & (d, 300% scaled b) with VF1, FD10, Truth = 1.000; the best solution for (*P1* & *P3*) (c) with VF4, FD15, Truth = 0.952.

supplementary material). Mean Truth(*P1*) was the best for FD20 instead FD15. When Truth(*P1* & *P3*) is concerned, though FD20 did not cause the objects to move outside the plane boundaries, the difference between FD15 and FD20 was statistically insignificant (TABLE A.XX in supplementary material). Thus, the result is qualitatively consistent with randomly generated 5% density relationships.

The best solution scatter plots illustrated in Fig. 4(b), (c), and (d) show that this study algorithm provides a layout that is much closer to the original known structure than our previous proposal based solely on *P1*. As in the results regarding random relationships, also here, the procedure involving *P1* & *P3* leads to a much less cluttered solution. To make comparable assessment, the best Truth(*P1*) layout had to be scaled-up by 300%.

C. Designing Sustainable Real-Life Manufacturing System – compound objects of various sizes

The simulation analyses conducted so far have focused on issues of sustainable layout design at a general level and have been rather theoretical in nature. The third set of experimental simulations involved the real-life example presented originally in the work of Tompkins [32]. They applied their FL algorithm for designing a production system comprising eight departments of various sizes. In our simulations of this example, a single grid module of the original departments' model corresponded to an individual object (agent). Each department includes one input/output element, which is artificially connected to the others. The input/output components are linked to each other according to the objective intensity of transport operations. Connections within departments are defined at a level twice as high as the highest transport connection to prevent the disintegration of departments. The original solution reproduced in our software along with the relationship values used in further simulations are shown in Fig. 5(a).

1. Experimental Design and Procedure

Consistent with our previous approach, we examined two independent variables, FD (SMALL_DISTANCE), and VF, maintaining five levels for each factor and an identical definition of the POSITIVE variable. We conducted 30 simulations for each experimental condition and two optimization methods. The outcomes, excluding configurations with objects outside the defined plane, were again analyzed by a two-way analysis of variance along with post-hoc tests.

2. Results

Mean truth values along with ANOVA statistics for both approaches are provided in Fig. 13 and relevant post-hoc test outcomes are collected in supplementary material TABLES A.XXI and A.XXII. The Tompkins [32] example relationship density is almost 10%, and the number of objects is close to 36. Therefore, the obtained results can be confronted with our previous simulations regarding randomly generated relationships with a 10% density for layouts comprising 36 elements.

The average solutions for the Truth(*P1*) criterion exhibit qualitative identical pattern with the corresponding layout with random relationships. The goal function decreases while the VF

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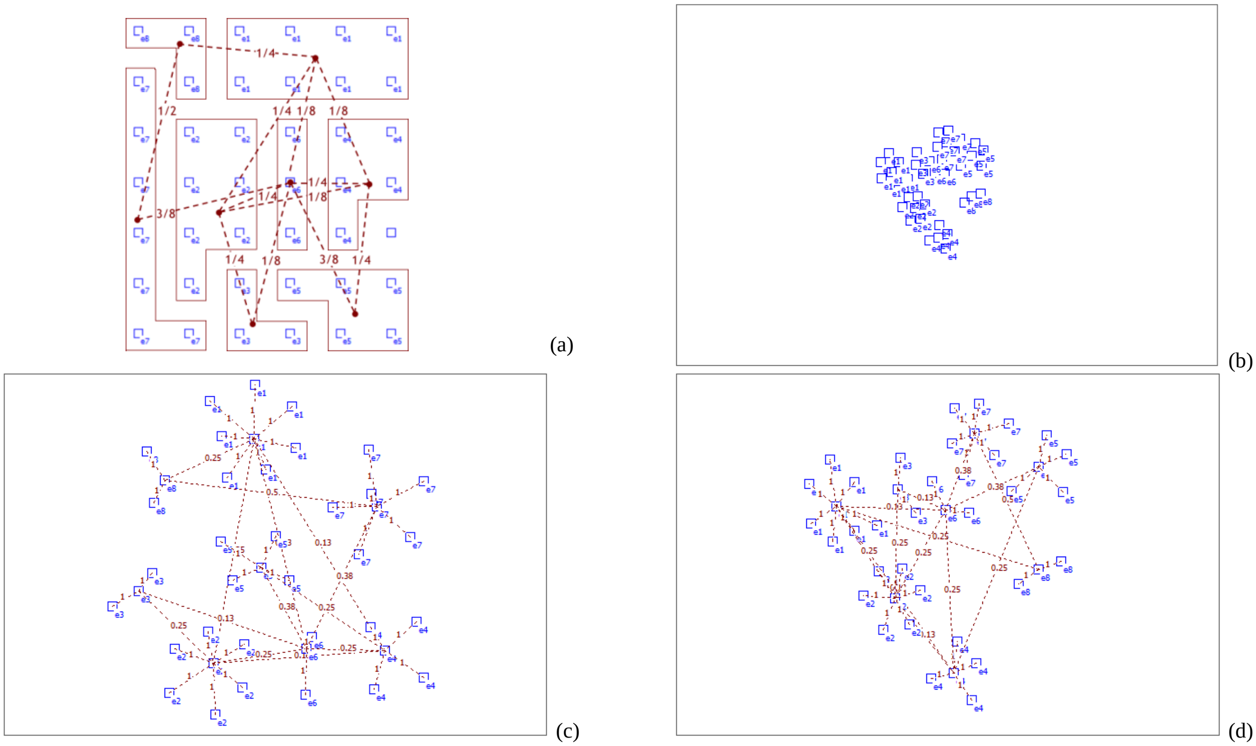

Fig. 5. The best solution for the example from Tompkins work [32] on the modular grid for centroids (a); the best solution for *P1* (b) & (d, 150% scaled b) with VF1, FD20, Truth = 1.000; the best solution for (*P1* & *P3*) (c) with VF4, FD15, Truth = 0.936.

is bigger and bigger and the best SMALL_DISTANCE variant is FD20.

Scatter plots obtained for Tompkins [32] example by the current study approach in comparison with random relationships layouts have mean truths somewhat different. The best VF amounted to 2% or 3% (with no statistical difference), however the bigger value was meaningfully worse (compare TABLE A.XXI). In previous simulations further increase in VF did not negatively influence the outcomes. When it comes to SMALL_DISTANCE factor levels, FD15 outperforms other variants both in the Tompkins [32] example and in the layout with random 10% relationships. On the other hand, FD20 performs worse in Tompkins [32] case and does not show a significant difference from FD15 in the case of random relationships (TABLE A.XX). Unlike configurations including random relationships, there is no significant interaction between VF and FD for Truth(*P1* & *P3*).

Our best scatter plot solution to the example from Tompkins work [32] with the highest degree of truth fulfilling *P1* and the conjunction of *P1* & *P3* are demonstrated in Fig. 5(b) and (c), respectively.

A cursory comparison of solutions obtained through both versions of our method shows qualitatively similar mutual arrangements of modeled departments to the best solution on the modular grid presented in [32]. However, the quality of the obtained solution stimulated by the conjunction of *P1* & *P3* is better than the one resulting only from *P1*. Moreover, one can notice that the scaled-up version of the layout obtained by the *P1* based algorithm corresponds astonishingly well to the best solution provided according to the conjunction of *P1* & *P3* in terms of its relative structure.

D. Designing sustainable real-life workstations – the role of non-linear membership functions

In addition to the previous experiment, this section further investigates the application of our proposal to real-life situations. We bring our considerations down to the lowest level of manufacturing involving the design of an industrial boiler operator [33]. This is the medium size problem with object dimensions specified in natural units. The input data of this example is provided in supplementary material in Fig. A.14. It also shows the arrangement which is an optimal solution in terms of the total hand travel distance during the operation cycle.

Analyzing the assumptions and goals of sustainable design, it can be observed that such an approach considers only the economic, (in this context, biomechanical) aspect. Apart from this important criterion, there are, however, additional factors influencing the overall quality of the operator's work and their well-being. One of these is the visual quality of the layout, understood as the alignment of the design with the basic principles and rules of human visual activity.

Many of the rules stem from the visual structure and physiology of vision, such as the appropriate grouping of related elements [35]. They arise from mechanisms of image processing, often preattentive [36], captured in Gestalt psychology principles like proper proximity of interface objects [37]. User experience and personal preferences significantly influence the adaptation of the interaction to the human user. These can be modeled by appropriate definitions of the membership functions for fuzzy variables used in our approach.

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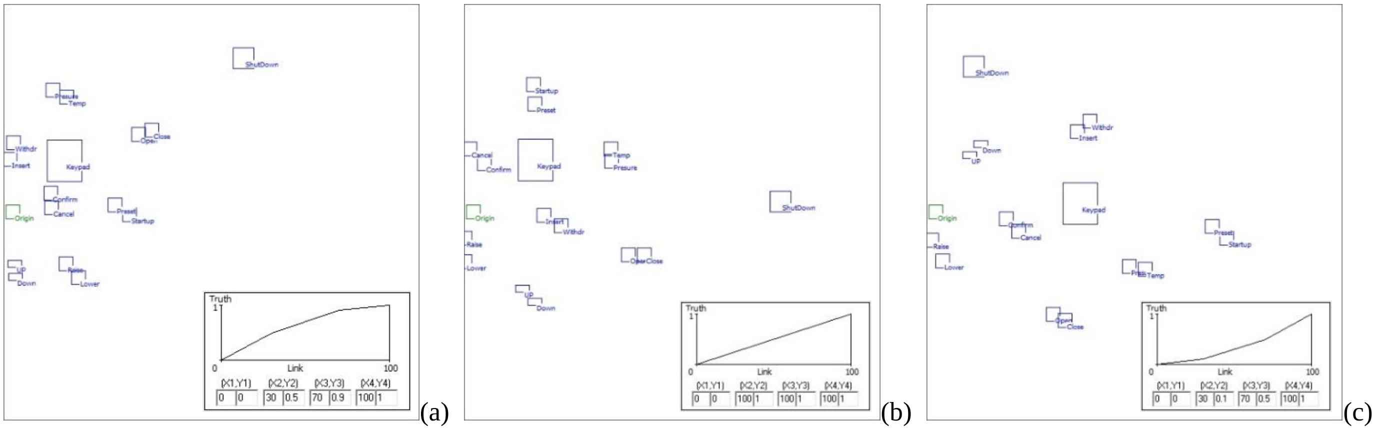

Fig. 6. Boiler console example best layouts for three different relationship membership functions (FD20): (a) convex (VF1) – Truth(*P1* & *P3*)=0.874, HCD=37.0m, R^2=0.64; (b) linear (VF1) – Truth(*P1* & *P3*)=0.926, HCD=39.5m; R^2=0.56; (c) concave (VF3) – Truth(*P1* & *P3*)=0.954, HCD=47.8m; R^2=0.61. (HCD – distance covered by hand).

Such definitions were included in these simulations as additional experimental factors.

We designed and conducted a series of simulation experiments aimed at generating the best scatter plots for this layout example with various parameters.

1. *Experimental Design and Procedure*

Experimental design and procedure was similar to previously conducted simulations (Fig. A.5 in supplementary material). In addition to previous simulation experiments, we assumed that an experienced operator might subjectively assess the necessity of proximity for individual pairs of objects non-linearly. This means that the objective number of hand movements might have greater or lesser significance in the subjective definition of proximity necessity based on experience and individual preferences. The non-linearity of subjective assessments in response to stimuli is confirmed in many psychophysiological studies. Therefore, we considered not only linear but also convex and concave membership functions for relationships – now understood as subjective proximity necessity.

Thus, the final experiment design included the following factors and their levels: Agent VF step: VF1, VF2, VF3, VF4, VF5; Distance membership function definitions: FD05, FD10, FD15, FD20; Positive relationship definition – linear, convex, concave (the detailed definitions are shown in Figs. A.15-A.17.). We used two types of LP algorithms as in previous simulations.

In this experiment, the size of an object is considered along with the NEUTRAL_ZONE variable. If NEUTRAL_ZONE is smaller than the object's size (defined as the radius of the inscribed circle), a virtual repulsive force acts earlier, and the attraction ceases. In the original study on boiler panel, a specific starting object based on the most frequent hand position at the beginning of the work cycle (denoted as *Origin*) was assumed. This object did not change its location during our simulations.

In addition to evaluating truth patterns, we calculated the values of R square (see section V) and the classical economic objective function for each configuration as the sum of the products of relationships and distances in physical instead of relative units. The latter criterion reflects, for instance, the total transport distance, total hand movement distance (HCD), actual operating cost, etc.

For each of the 36 experiment conditions we performed 30 simulation runs of our approach, recording the most significant parameters and the best scatter plots.

2. *Results*

Classical ANOVA results revealed significant ($p < 0.0001$) differences between mean truth values depending on the examined factors for both types of LP based algorithms. The graphical illustration of these differences are presented in Figs. A.19 and A.20 in the supplementary material. Changes in truth values with respect to the fuzzy distance and virtual force step effects exhibit, in general, similar patterns as in previous experiments. Although the relationship membership function factor was statistically meaningful for both LP-based approaches, its significance was considerably bigger for LP involving (P1&P3). In this case the concave variant allowed for obtaining markedly larger truths than linear or convex variants. The data visualizations clearly shows that almost in all experimental conditions, the best truths were obtained for the FD20 fuzzy distance membership function. Thus, detailed post hoc tests were conducted for this factor level and presented in TABLES A.XXIII-A.XXV.

Analyzing results for the convex variant and P1, VF2, VF3, and VF4 provided the highest mean truth values that did not significantly differ from each other. The best results for the linear version and P1 were obtained by both VF3 and VF4, while for the concave version, VF3, VF4, and VF5 were equally good at generating the best solutions

When P1&P3 are concerned, VF1 turned out to be the best setting for the convex variant. However, this value was the worst for the concave membership function, with other VF values providing statistically similar mean results. In the linear case, there were no significant differences between any of the VF values ($p > 0.05$).

Interesting conclusions can be drawn from the qualitative analysis of the best solutions obtained in these simulations. For instance, Fig. 6 shows scatter plots that are the best in terms of the Truth(*P1* & *P3*) and all three membership functions. The best solution for the convex relationship (Fig. 6(a)) can be considered the most sustainable in terms of the operator's energy expenditure. The hand travel distance in such an interface is the shortest. Conversely, the best layout for the concave function (Fig. 6(c)) helps avoid errors and eye fatigue due to the clear separation of object groups. This proposal also shows even utilization of the area occupied by objects on the design plane. The solution for the linear membership function (Fig. 6(b)) is intermediate, but it is worth noting the lower R^2 value compared to the previous results, indicating a less significant correspondence between the distances of object pairs and their relationships. Qualitatively similar behaviour can be noticed for the LP based on *P1*, which is illustrated in Fig A.18 in the supplementary material. In general, not very large changes in the shape of the membership function cause noticeable qualitative changes in the proposed solutions.

V. COMPARISONS WITH OTHER SCATTER PLOT APPROACHES

In the analyses from Subsections IV.A – IV.D, we documented the differences in the structures of scatter plots resulting from the application of two different approaches to defining linguistic patterns and their definitions. The basis for comparison so far has been the truth values of the used patterns. Applying such an approach to scatter plots obtained by other methods is not directly possible. To compare solutions obtained in our approach with other scatter plot generating methods, we apply an indicator based on correspondence between object distances and their relationships. It seems that, a good overall quality measure for this purpose is R-square (R^2) calculated for the linear regression of relationships depending on distances. In such a case, R-square shows to what extent the relationship variance is explained by distances. This indicator does not depend on the scale or units adopted for the project.

In TABLE I, we have summarized the comparison of R^2 values computed for the best solutions obtained in our approach using *P1* & *P3* with those generated by the Multidimensional Scaling (MDS) method and the Drezner algorithm. The results document the significant advantage of the proposed approach in reproducing correspondence from the relationship matrix in scatter plots. The two classical approaches are very sensitive to the structure of object relationships. In contrast, our methodology maintains far-reaching stability. It consistently reproduces relationships in scatter plots with proportional effectiveness. This mainly depends on the density of relationships and the problem size.

It is also worth pointing out the general qualitative feature that differentiates classical solutions from the results of agent-based scatter plots (Figs. A.21 and A.22). The objects in these solutions are more evenly distributed. This is typical for all examined tasks, including those with known structures and rational relationships. Apart from the Tompkins [32] example, all these layouts have a higher R^2 indicator, meaning the distances between object pairs better reflect the relationships.

The obtained results also show some instability of the examined classical methods, or their strong sensitivity to data structures. In the production design problem, the Drezner algorithm finds a better configuration than our LP methodology. However, in the similar Boiler example, the MDS technique generates a significantly better result than the Drezner approach. Surprisingly, the MDS method fails in reproducing the relationship structure for the production design task. Both classic approaches occurred to be useless for designing the boiler console.

Additionally, the failure to consider object sizes in classical algorithms causes many analyzed cases to have unreadable layouts due to placing many objects almost in the same locations.

VI. DISCUSSION

The analysis of the obtained results indicates primarily significant qualitative differences in the behavior of algorithms according to *P1* and the criterion that combines *P1* & *P3*. The forces generated strongly encourage closely related pairs to approach each other in every single step, until the pattern is fully true or the forces are balanced. Therefore, in the scatter plots generated according to *P1*, objects with strong relationships are next to each other. However, they are also in close proximity to those elements that appear as *neutral* to *P1*. Thus, their position is not taken into account during the optimization process. Regardless of the distance definition, the plots in this case are clearly more *densely populated* than those obtained through the second approach determined by the approach introduced in the present study. The latter pattern determines the *well-being* of components by also taking into account neutral and/or weakly related neighbors in the following way: if an object is close to another, they are strongly related. The virtual force associated with this situation causes mutual repulsion between them if they are not connected. Therefore, in final scatter plots, considerably greater dispersion of objects can be observed.

A. Implications for Sustainable Manufacturing Systems Design

The results of conducted simulation studies reveal a convergence of the proposed methodology with both the general idea of SDGs (Sustainable Development Goals) and the specific challenges of this philosophy in the design of production systems. By utilizing the proposed concepts, an expert can articulate their requirements for the arrangement of production system elements or workplace components in expressions similar to natural language. Both the linguistic

TABLE I. COMPARISON OF DREZNER, MDS, LP(*P1*) AND LP(*P1* & *P3*) ALGORITHMS BY USING R SQUARE MEASURE.

	Random 4×4			**Random 6×6**			**Random 8×8**			**Known structure 6×6**	**Known structure 10×10**	**Production layout**	**Boiler panel**
	15%	10%	5%	15%	10%	5%	15%	10%	5%				
Drezner	0.36	0.0	0.0	0.29	0.26	0.84	0.28	0.29	0.28	0.47	0.42	0.28	0.05
MDS	0.43	0.36	0.33	0.07	0.03	0.20	0.70	0.08	0.01	0.07	0.05	0.70	0.02
LP (P1)	0.71	0.97	0.98	0.34	0.54	0.76	0.15	0.25	0.33	0.71	0.63	0.81	0.75
LP (P1&P3)	0.82	0.97	0.98	0.35	0.51	0.83	0.78	0.33	0.41	0.81	0.71	0.78	0.63

patterns used and the definitions of relationships between objects can be tailored to meet the requirements of sustainable solutions represented by obtained scatter plots.

In practical applications presented in Sections IV.C and IV.D, we have shown how the obtained scatter plot can help in achieving sustainability goals on two different levels. They translate to tangible sustainability goals by minimizing the chosen layout quality criteria. Depending on whether the decision maker bigger focus is to minimize the space occupied by all objects or their even distribution over the available area, the designer can employ the specific LP-based algorithm.

Analyses of the conducted simulations showed, in particular, that relying solely on economically oriented requirements formulated by *P1* leads to dense scatter plot structures minimizing surface utilization. Such an approach may form the basis for analysis and decision-making in situations where this increased density has no adverse effects on the functioning of the production or logistics system (e.g., automated production lines). On the other hand, applying the present approach with combined *P1* & *P3* leads to a qualitatively more even distribution of elements in scatter plots with a transparent structure, utilizing a larger area of the available design space.

This type of *hint* for the designer aligns well with the earlier postulates of considering the safety and well-being of production system workers. This approach also seems particularly relevant for the analysis and design of interactive systems, where greater transparency of interface structures enhances their usability.

The discussed research simulation experiments were conducted in successive steps, which can be summarized as a kind of guide describing the use of our application in the process of designing sustainable layouts. Its general stages involve: preparing initial data, gathering expert knowledge, designing simulation experiment, analyzing the results, and determining the final solution. The proposed detailed scheme of such a procedure can be presented as a process shown in Fig. A.5 of the supplementary material.

B. Prospect Studies

The presented concepts and their potential capabilities encourage further research. It seems that a relatively simple and flexible system design can be expanded in several directions.

An interesting direction for further research and development of the proposed approach is taking advantage of the flexibility in formulating other linguistic patterns. They can represent various important quality criteria in FL projects in production, logistics, human computer interaction or other areas. A natural consequence of such research is also the search for relationships between layout quality and the ways of specifying linguistic variables describing the parameters of the defined patterns by experts.

It is also worth considering expanding the base of linguistic patterns with other criteria to broaden the evaluation of obtained solutions in real design contexts. The sphere related to the well-being of workers, such as job satisfaction and aesthetics, appears to be a particularly suitable area for such an extension. The soft nature of these criteria and relationships aligns well with the linguistic character of patterns and variables in our approach.

Next, the analyses conducted here considered only the linear nature of the fuzzy representation of linguistic variables. The use of other functions may impact simulation results, which is also essential to investigate due to suggestions from psychological studies about the non-linearity of human reactions to certain stimuli.

Finally, the obtained results from experimental studies indicate that, for practical reasons, it is worthwhile to consider supplementing the concept with a kind of expert system suggesting simulation parameters for a defined deployment problem. Statistically significant differences in the quality of solutions obtained with different combinations of simulation parameters for specific matrix structures are evident.

VII. CONCLUSION

The research aims to address the predominant focus on qualitative aspects in existing literature by introducing more quantitative approaches, particularly those utilizing imprecise and uncertain data. The proposed methodology employs linguistic patterns with a fuzzy background to optimize decision-making processes in sustainable manufacturing systems. This approach allows for the formal and systematic application of expert knowledge, bridging the gap between qualitative and quantitative methodologies.

The main contributions of the paper include the proposal of a novel method for solving the FLP using scatter plots without predefined object locations. This method involves smart optimization based on linguistic patterns with fuzzy variable definitions. The study extends a previous model by introducing additional criteria, altering significantly the behavior of objects compared to the previous version.

The research conducts a comprehensive examination of the proposed method through simulation experiments, including artificial problems, designs with known optimal solutions, and real-life examples. The results of simulations with randomly generated relationships provide recommendations for specifying parameters in real-life problems. Additionally, the paper conducts a simulation-based analysis of a previous method, assessing its sensitivity to changes in parameter definitions and comparing it with the newly proposed model.

The paper demonstrates how scatter plot solutions to the FLP, generated through linguistic pattern-based optimization criteria, can be utilized as a tool for supporting sustainable manufacturing. Such a way of investigating solutions for the facilities layout problems represented as scatter plots undoubtedly facilitates the evaluation of the quality of obtained layouts. Although the plots do not necessary directly deliver the final layout, they can provide a fairly precise and clear indication for designers, especially when using the conjunction of *P1* & *P3*.

The study discusses the qualitative and quantitative data on the types of scatter plots generated by two versions of linguistic pattern-based optimization criteria, offering insights into designing manufacturing systems that align with specific sustainability goals. In general, the current paper approach provides better solutions with respect to even, and thus more sustainable utilization of available space. This feature can be further tailored to the designer needs by appropriately specifying relationship membership functions. Convex membership functions allow for modelling the situation when experts taking into account their practical experience may favor layouts with shorter distances between objects at the cost of more cluttered layout design – more sustainable according to a distance criterion. On the other hand, concave membership functions can reflect situation that possibly even object distribution over the available space – more sustainable according to the more spatially balanced layout criterion.

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