

A Decision Support Framework for FLP in the Context of Industrial Facilities by the Use of BIM

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In today's industrial production environment, an effective solution to the FLP (Facility Layout Problem) plays a significant role in deciding whether a facility will hold a competitive advantage against others by its improved workflow. This advantage comes from an efficient placement of facilities, which mostly contributes to the overall business performance. In addition to that, regarding the need to answer the demands of the dynamic market, facilities need to adapt their processes and adapt their production line as quickly as possible. Therefore, a continuous search for a solution to the FLP is present. Although there are many space allocation programs available both as academic and commercial products, present approaches' availability in the BIM environment is not common yet. This paper introduces a decision support system framework which uses Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) to generate the most appropriate solution in Revit Dynamo environment both in the earlier phases of design and through the life-cycle of the facility. The proposed framework will specifically be responsible for generating solutions for equipment location in serial production facilities. As NSGA-II is a Multi-Objective Evolutionary Algorithm (MOEA), a second optimization criterion is defined as the optimization of the foreman's locations distributed on the shop floor. A Dynamo package named Refinery will hold the optimization and evaluation procedures.

Keywords: Facility Layout Problems, NSGA-II, Automated Space Layout

INTRODUCTION

Manufacturing methods have been changing tremendously by the advent of Industry 4.0 concept, the way we build and plan have also been changing. If Industry 4.0 is a concept identified by the digitalization and automatization of production processes, its equivalent in the construction industry can be attributed to BIM technology which is mostly adopted by AEC (Architecture Engineering Construc-

tion) professionals. When appropriately utilized in the era of Industry 4.0, BIM promises to deliver high efficiency; therefore, value for owners and managers of facilities. Approaching the industrial facility design from three ways, it can be seen that there are three interdependent teams which are AEC, industrial engineering and managerial teams. Inefficiency issues arise when one of these teams' work is inadequate, planned poorly, or in a low co-operation

with the others. For the co-operation of AEC and industrial engineers, most layout tools commercially available use a two-dimensional representation of the manufacturing facility which is not adequate to describe some situations during the design process (Smith and Heim 1999). Besides the performance criteria need to be fulfilled by engineering issues in the shop floor, the third dimension especially becomes an issue considering the architectural setup of the facility whereas predefined equipment allocation is directly related with the system design of the facility (Heating Ventilating and Air Conditioning (HVAC) systems, drainage issues, circuit design, etc.). At this point, BIM can supplement the two-dimensional layout by enabling the designers to work directly inside a three-dimensional environment, so to take rapid and accurate decisions that result with fewer clash issues of integrated systems such between structural elements and machines or between HVAC systems and machines. For the management team, it can help to analyze the current needs and to foresee future expenditures. BIM for Facility Management is already being used for healthcare and educational facilities, but its use should also be emphasized for industrial facilities since it can help save time and money by its ability to store information which can aid space allocation, asset management and maintenance tasks of the facility (Marchese and Ruderow url1). Furthermore, the influence of BIM's presence in all phases of a life-cycle of a building on the collaboration of architects, engineers, and facility managers should be taken into consideration in today's ever-changing nature of facilities. So, in the context of this paper, BIM presents a way to intersect industrial engineers, operational management, and space planning professionals by combining their respective expertise in quantitative and qualitative measures.

The paper named 'The Spatial Culture of Factories' by Peponis (Peponis 1985), where Peponis asserts that there are qualitative measures along with quantitative measures in a manufacturing facility which also was a starting point of this paper to further investigate the issue, to find a shared domain

to meet architects, engineers, and facility managers which eventually led to the creation of a workflow. Another promising line of question is whether this workflow can be implemented inside the BIM environment. As a result, two questions are addressed:

- Can multi-objective evolutionary algorithms (MOEAs) intersect different stakeholders in a manufacturing facility design?
- Can this workflow be implemented inside the BIM environment through the use of a visual programming tool, namely Dynamo?

Answers to these two questions are also thought to define the originality of this paper.

The purpose of this paper is to identify and develop a workflow which can offer an alternative approach in the optimization of factory layouts both upon the early design phase and during the refurbishment phases. First of all, to understand the FLP through an engineers view, a brief background study on the problem and its solution methods is being reviewed, which can be seen in section 2. Building a foundation through section 2, a framework to help the space planners and managers is proposed in section 3. After the proposal, to test the proposed workflow, a custom-made steel parts manufacturing facility (which as a case is believed to support the idea of contributing to the era of Industry 4.0) is taken as the case study and a preliminary BIM model is generated for their new factory building, where the proposed algorithm is tested. The obtained results through the application of optimization tool Refinery are shared in section 4.

BACKGROUND

As research on manufacturing systems show that 20-50% of a product's cost can be attributed to material-handling expenses (Tompkins et al. 1996) whereas it marks the importance of the consideration of facilities' physical arrangement. The configuration of the manufacturing space, which will be defined as Shop Floor (Pinto et al. 2016). plays an essential role in the efficiency of the production process. Reducing the

required floor area by creating fewer process steps can benefit plants by means of efficiency. To simplify and reduce the flow of a process, industrial engineers especially work on equipment allocation problem as it is called as a Facility Layout Problem (FLP) (Kusiak and Heragu 1987). In a new facility design or every time an adaptation is needed in cases like any new input such as an addition of new equipment, change in the number of staff or change of work process necessitate developing a new solution for FLP. Therefore, FLP covers both design and life cycle processes. So this brings forth the problem statement as if FLPs can be solved iteratively through the use of generative design tools. Especially the growing demand for customized products shows the need for a revolution in the production processes.

Over time, an extensive literature has developed on FLP. In order to understand the formulation types of the problem and solution procedures amongst the vast amount of research on this area, together with the recent surveys (Singh and Sharma 2006; Drira et al. 2007) earlier surveys (Levary and Kalchik 1985; Kusiak and Heragu 1987; Meller and Gau 1996) are being taken into account in the context of this paper. Having an architectural background and for presenting the idea to the common domain of engineers and architects, technical terms are being presented briefly in this section.

Layout Types

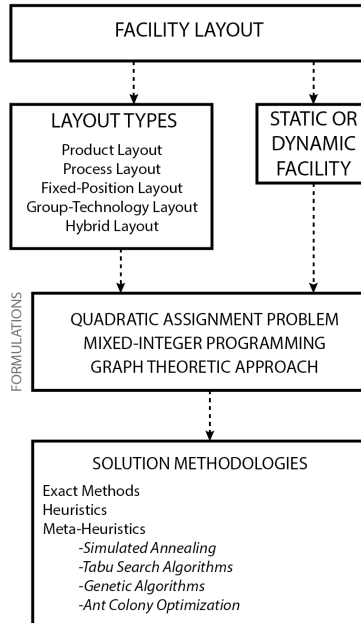
Heragu states that there are five types of layout in manufacturing systems according to their product variety and volume: product layout, process layout, fixed-position layout, group technology (GT)-based layout and hybrid layout (Heragu 2008). Since the manufacturing facility chosen for the case study produces a wide range of custom-parts in small quantities and needs a flexible workflow, process-layout is chosen to start as a model. Despite the disadvantage of this layout type because of the increased material-handling costs and long product queues, it is aimed to aid these with the proposed algorithm.

Formulations of the Facility Layout Problem

Because many researchers cannot define an exact formulation of the FLP, mathematical models as most knowns are formulated as quadratic assignment problem, mixed integer programming (MIP) and graph theoretic approach. Heragu and Kusiak assert that the disadvantage of the both QAP and MIP models is their requirement of initial locations for assigning the facilities, and not being able to solve large scale layout problems (Heragu and Kusiak 1990). On the other hand, the graph-theoretic approach is more suitable for the defined framework as a two-step process where the first step is to generate a planar graph which reflects the adjacencies from the relationship diagram, that is shown as nodes and secondly generate a block plan which is the dual representation of the planar graph, where drawn lines between the nodes are the adjacency requirements between the machines in the context of this paper.

Solution Methodologies

Much like space planning problems in architecture, facility layout problem requires the search for a satisfactory solution for multiple objectives. Since exact methods and heuristics are not suitable for bigger size problems as the case study requires, they are not being reviewed. And among meta-heuristics, multi-objective evolutionary algorithms under genetic algorithm is chosen. Because, FLP belongs to the category of the multi-objective optimization problem (Shah et al., 2010). These objectives mostly conflict with each other. In quantitative objectives, material handling cost (MHC) can be attributed as one of the most used criteria while the closeness ratings, safety planning for workers, resting and communicating areas, etc. can be counted in qualitative criterions. In the study, these objectives are the material handling costs (MHC), adjacency satisfaction rates and as the qualitative objectives, foremen field of views (FOV) which are tested as sets of two objectives at one time because visualizing the Pareto front becomes harder with three or more objectives.



Group Name	Description
Creation of a Schedule	Planned Workflow is mapped to adjacency scores.
Mapping Adjacency Scores	Manual Conversion of MS Project workflow diagram to adjacency scores in Microsoft Excel
Input of Properties	Defining Machine Properties
Transform Grid	Revit grid system is converted to the Dynamo coordinate system to locate the cuboids and foremen.
Organization & Recheck of Data	Excel Data is imported and organized inside the Dynamo Environment
Initial Cuboid Placement	Initial Cuboids (machines) are created, and the same type of machines are distanced from each other.
Foremen Location & Isovist Map Generation	Foremen Locations and Isovist Maps representing Foremen Field of View are created.
Defining Conditionals	Cuboids are painted red if adjacency ratios are not met. Surface representing Field of View (FOV) is painted blue if the required ratio is not met.
Optimization Phase	Refinery Server begins the optimization.

To sum up this section, figure 1 can be helpful to overview the steps to divide a facility layout problem into.

A FRAMEWORK PROPOSAL FOR A FACTORY FLOOR LAYOUT DESIGN

In this section, a decision support system framework which uses Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) to generate the most appropriate solution in Revit Dynamo environment in the earlier phases of facility design is proposed. Specifically, the proposed framework will be responsible for generating equipment locations in serial production facilities and foremen locations relative to the equipment locations in order to enhance productivity. Optimization process will work towards minimizing the material handling cost while maximizing the field of view of the foremen. The efficiency of the proposed approach is evaluated with the Pareto Optimal Set results, which are produced by the Refinery package inside the Dynamo. Grounding its background knowledge on Project Fractal (Autodesk) and The Living (Autodesk Research Lab), Project Refinery is an optimization and optimization engine which works inside Dynamo (Walmsley Url2).

Mainly categorized under two operations, various software had been used and is proposed in this paper. These operations differ both as the user type that manages it and the tasks they achieve. Moreover, Microsoft Excel and Microsoft Project are being proposed as being used by the planning/management team while the Autodesk products consecutively Revit, Dynamo, and Refinery are for the use of the layout designer/architects mostly. Table 1 demonstrates the proposed workflow scheme's interpretation with the software tools which are preferred by the author of this paper.

Creating Required Information Before Dynamo Phase

Dynamo Graph provided along the case study needs input data from the external sources, which are the database and project management tools respectively

Figure 1
Solution Scheme
for FLP

Table 1
Proposed Workflow

Figure 2
Scheme of the
Proposed Workflow
with Software Tools.

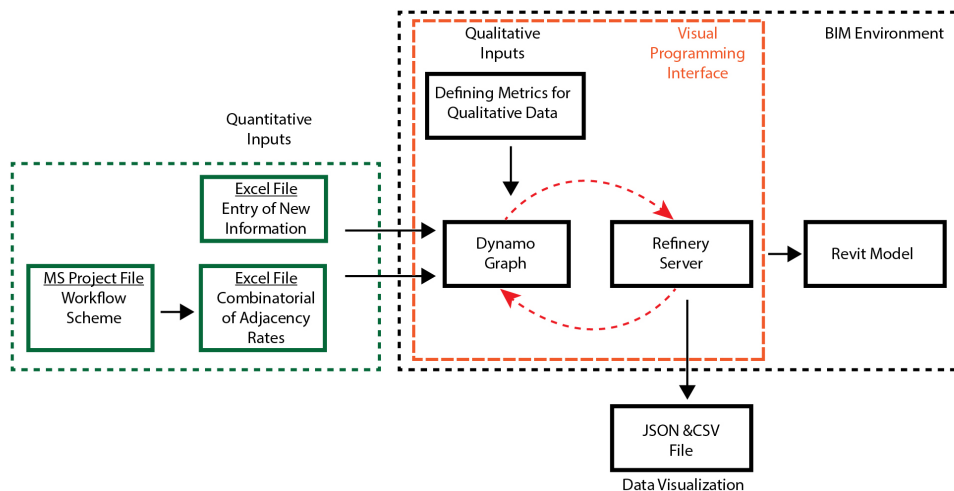
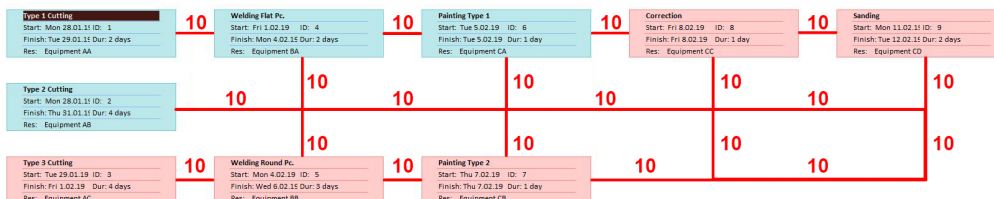


Figure 3
Manual Ratio Entry
Logic from the
Project Workflow.



named as Excel and Microsoft Project. As a process layout is being tested in the study, machines are arranged according to the processes they perform. Activities from the project schedule are mapped to the corresponding machines. After generating a timeline for the process, the workflow scheme is rendered inside the MS Project software, which the user can also modify (Figure 3). On the other hand, Microsoft Excel is used for two operations. First is the modification of the properties of the machines such as dimensional values, workers' capacity around the machine, etc., where these features will start the optimization each time the user hits the 'save' button. Second, is the

mapping of the adjacency ratios obtained from the workflow scheme at the Microsoft Project file. Figure 4 shows the way network diagram in MS Project influences the adjacency ratios between the machines. The logic here is that the distance is relative to the sequential order of the machines.

Preparation of the Building Information Model

As the case study is worked through an early design phase of the factory, a low LOD (Level of Detail) model is prepared inside Revit. A plan and a perspective view of the factory floor will be enough to

	EquipmentAA	EquipmentAB	EquipmentAB	EquipmentAC	EquipmentBA	EquipmentBB	EquipmentBB	EquipmentBB	EquipmentCA	EquipmentCB	EquipmentCC	EquipmentCD	EquipmentCD	EquipmentCD	EquipmentCD	EquipmentCD	EquipmentCD
EquipmentAA		10	10	20	10	30	30	30	20	40	30	40	40	40	40	40	40
EquipmentAB	10	-	10	10	20	20	20	20	30	30	40	50	50	50	50	50	50
EquipmentAB	10	10	-	10	20	20	20	20	30	30	40	50	50	50	50	50	50
EquipmentAC	20	10	10	-	30	10	10	10	40	20	50	30	30	30	30	30	30
EquipmentBA	10	20	20	30	-	20	20	20	30	30	20	30	30	30	30	30	30
EquipmentBB	30	20	20	10	20	-	10	10	30	10	40	50	50	50	50	50	50
EquipmentBB	30	20	20	10	20	10	-	10	30	10	40	50	50	50	50	50	50
EquipmentBB	30	20	20	10	20	10	10	-	30	10	40	50	50	50	50	50	50
EquipmentCA	20	30	30	40	10	30	30	30	-	20	10	20	20	20	20	20	20
EquipmentCB	40	30	30	20	30	10	10	10	20	-	30	40	40	40	40	40	40
EquipmentCC	30	40	40	50	40	40	40	40	10	30	-	10	10	10	10	10	10
EquipmentCD	40	50	50	30	30	50	50	50	20	40	10	-	10	10	10	10	10
EquipmentCD	40	50	50	30	30	50	50	50	20	40	10	10	-	10	10	10	10
EquipmentCD	40	50	50	30	30	50	50	50	20	40	10	10	10	-	10	10	10
EquipmentCD	40	50	50	30	30	50	50	50	20	40	10	10	10	10	-	10	10
EquipmentCD	40	50	50	30	30	50	50	50	20	40	10	10	10	10	10	-	10
EquipmentCD	40	50	50	30	30	50	50	50	20	40	10	10	10	10	10	10	-

Figure 4
Excel Table of the
Adjacency Scores.

view and analyze the optimization process. Since a system design, including the mechanical, electrical, and structural considerations is not involved at this stage, section views or other representations are not included at this paper. Grids and the factory floor surface are the two elements that will be used as inputs to the Dynamo graph. Columns, walls, and sectional doors are excluded from the clash test, but it should be noted that machines clash test with these elements can be considered for the future works.

Initial Cuboid Locations on the Factory Floor

It is important to note that the machines (the equipment) are being referred to as cuboids in this graph as their representational equivalent. Because neighborhood relations of the cuboids are being set by the circle packing method, cuboids center points (centroids) are going to be the first matter of the following operations in this section. Since the placement and evaluation of this placement are utilized by the genetic algorithms (GA), the only thing it requires is a random set of preliminary solutions to find reasonable solutions. For that reason, the first step in this section is to use the resulting point list from the coordinate system as the base points for the cuboids to locate on. In the main model, points set consists of 7344 points, and the 16 cuboids will place on this set randomly. However, the equipment with multiple quantities is not being generated in the first phase. The reason to do this way is that the layout type is being set as a ‘process layout’ for this case study. In this layout type, all equipment performing the same process are placed together in one department (Her-

agu 2008). Therefore, one type of each equipment will be generated; then their multiples will be generated just like a mitotic division by a set of dimensional rules (figure 5). Remaining points on the coordinate system after the initial placement of the cuboids will be used for the first placement of the cylinders representing foremen rooms.

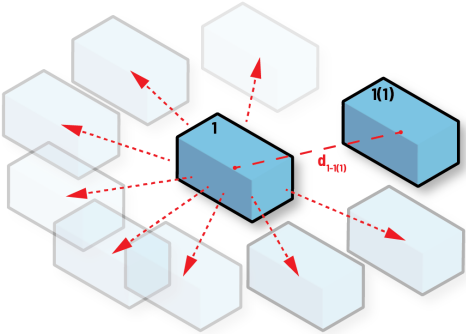


Figure 5
Equipment
generation from
parent equipment.

Foremen Locations & Isovist Map Generation

As being the second optimization goal of the proposed algorithm, foremen rooms are planned to be located on critical points where they can employ a satisfactory field of view. For that reason, parameterization of the generation of their location is an essential part of the total graph. Two single foremen vintage points on the shop floor that interplays with equipment locations are defined. These points on the shop floor enable the creation of isovist maps that represent foremen's FOV. This boundary in this

study refers to the outer edges of the shop floor and obstacles in this spatial environment are the factory equipment that blocks the FOV of the foremen. Furthermore, observable angle of the foremen is set as 360 degrees as this refers to a full isovist. This can be modified due to the needs of the user in such cases like the geometrical properties of the room of the foremen is known, or the FOV of the human eye is set as a constraint. However, in this study, full isovist is preferred rather than a partial isovist.

Defining Conditionals & Restrictions

In this part of the algorithm, conditionals and restrictions are defined in order to communicate with the Refinery and directing the graph to represent the information needed to the human designer. There are two conditions and restrictions which also set rules for the solution space, through controlling it. First conditional sets the rule for machines allocation criteria. This conditional is informed with two graph chunks that reports distances between the machines and evaluates them in a considerable distance range. Firstly, machines distances against each other are reported as machines are pairwise. Secondly, these distances are tested if they are in a considerable range defined by their adjacency ratios. It is set here as the distance between the machines cannot be lesser than the euclidian distance obtained by the max value of the width/depth dimensions of each machine, plus the distance required for the circulation around them and this distance cannot be greater than the addition of the required adjacency rates to the previous summation. If the resulting layout meets all the adjacency measures, cuboids color remain default value, which is a grey color. Else, they are painted red. To empower this conditional, an output node for the Refinery to maximize that is explicitly created, which is named 'adjacency satisfaction rate.' This node tries to satisfy as much of the adjacency ratio between the solutions. Second conditional tests if the desired field of view (FOV) of foremen is achieved. If the FOV is greater than sixty percent for the shop floor, then the isovist surface is

painted green. Else it is painted blue.

Remaining rules are based on restrictions in which first of them is responsible for keeping all the equipment inside the factory boundary. Since machines try to find locations according to each other, in some conditions some of them move out of the boundary. A restriction co-operates with Refinery tries to maximize the number of machines to stay inside the boundaries while satisfying the adjacency rules to solve this problem. Second of these restrictions is to minimize the clash between the machines. As a result of using the centroids of the machines while locating them, machines can intersect in some positions. In order to solve this problem, a restriction node that co-operates with Refinery.

Optimization Phase

Given the constraints and input parameters to the Refinery, it is needed to define the input and output parameters where input parameters are the ones that Refinery plays with in order to find optimal solutions. In the optimization settings, the input of how many populations per how many generations should be produced should be defined. Test results are being reviewed due to their population number, and the performances of each will be compared in the following section. This comparison uses MHC in the X-axis, FOV in the Y-axis and Adjacency Satisfaction Rate (ASR) scores as represented by scaled color circles. It should be noted that MHC values are as million dollar units, and FOV is as percentages.

CASE STUDY: ANKARA CUSTOM STEEL PARTS MANUFACTURING COMPANY

Custom Steel Parts Manufacturing Factory is the case study subject of this paper, which is located in the Ankara region, in Turkey. The main activity held in this facility is based on delivering high-quality engineering products to complex custom steelworks orders. Steelworks such as a cement factories tall silo tower, a crane construction, etc. are amongst a few examples of the produced work here. Since customization is the key figure of this facility, there is a



Figure 6
Aerial Render of the
Factory Building
(Image Courtesy of
Aysegul Balkan
Architects).

constant need for a new layout with little cost and disruption to production as possible. Although the factory type might not be seen as a serial production facility, the volume of the work and the working scheme of this facility can easily be attributed to the former type.

In the time of this study, the factory building is being constructed, and it is hoped that the framework provided here will be of an example use not only for the initial layout but also for the future changes in the life-cycle of this building. Also, it should be noted that in this period a fixed valid equipment list is not shared, but the substantial activity zones and primary machines are shared.

Results

The results from the study are compared by the number of population in each generation. The scatter-plots and parallel coordinates plots provide this comparison. It is aimed to view different results by testing population numbers. As results suggest, as the popu-

lation in each generation increases, it is more likely to reach to near-optimal results. This deduction is also parallel with Aiello et al. 's work (2012). In the case study, it is parallel with achieving the most adjacency satisfaction rate (ASR). As the number of population increased, satisfactory values are obtained in adjacency satisfaction rate, and solutions moved closer to the Pareto Optimal concave as this can be seen in figure 7. However, the increase in the number of population also adds to the needed computational time. Amongst the obtained results with a different number of populations, two of the solutions from each are chosen as the relatively good solutions, and these are marked as Solution A and Solution B.

Obtained results show unsatisfactory solutions due to displaying the opposite of the initial expectation regarding the relationship between the material handling cost (MHC) and the FOV of foremen. As known of the goal of the study, the initial expectation was to minimize the material cost while maximizing the FOV as they were thought to be conflicting ob-

jectives. The resulting graph can be seen in Figure 7.

Figure 7
Optimization
Results (MHC /
FOV).

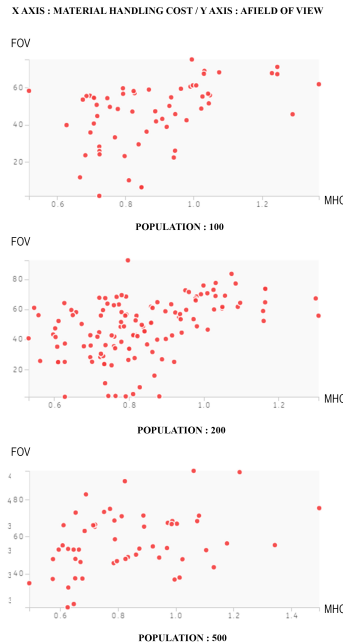


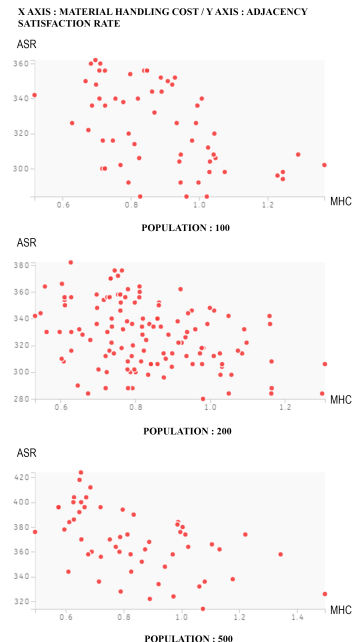
Figure 8
Optimization
Results (MHC / ASR).

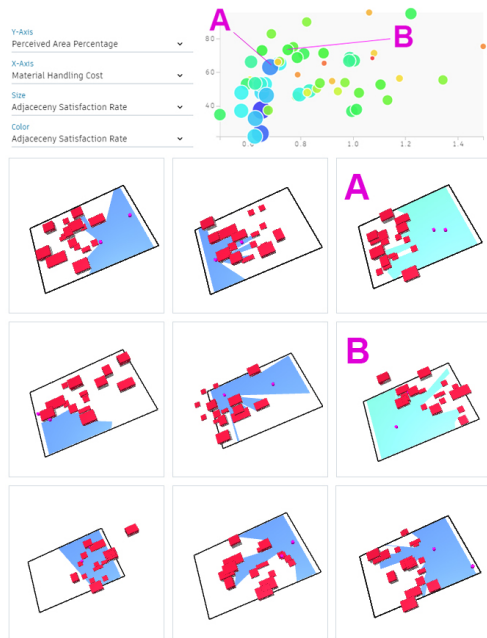
In addition to that, as the satisfied adjacency ratio decreased, the FOV value increased. So, it can be said that concave in this result is the mirror of the expected result. However, ASR and MHC resulted in a satisfactory way, as seen in (Figure 8), where the adjacency satisfaction rates are satisfied as the material handling costs are decreased. Moreover, ASR and FOV comparison showed what was initially the expected MHC-FOV relationship.

The resulting solution marked as solution A satisfied 412 conditions in 480. Comparing this result with optimization results of lower population number, it can be seen that this value is the maximum that is reached, and if more computation time is given, the exact rate can be obtained. The perspective view of the solution can be seen in Figure 9.

CONCLUSION

This paper aimed to describe a workflow and implement a framework for the industrial facility design. The proposed workflow is delivered through a visual programming interface for a new facility to be constructed in the near future. Use of an NSGA-II is used in order to search for the solution space is exhibited which is believed that will help designers to choose good design options. Although the results of this case study have been encouraging in terms of seeing many design alternatives, the proposed graph had imperfections in defining the objective functions for both qualitative and quantitative factors. To get better results, Refinery's inner NSGA-II working algorithm would be analyzed more, so objective functions would be more integrated within the Refinery program.





To aid this, it would be helpful to see different generations results on the scatterplot, which is not available in current Refinery build. Also, the fact that presented models are fairly abstract and oversimplified, rough geometry to be exact, results provided here far from defining the final layout design and needs refinement by the designer. But, this framework can be improved in the future by more accurate objective functions and advanced constraints. In conclusion, the proposed framework is thought to be a modern tool to support both architects and the engineers whom they collaborate with, in determining the most effective layouts for the machines or the departments inside a facility.

ACKNOWLEDGMENT

The authors would like to thank Aysegul Balkan Architecture and Birikim Mühendislik for their contribution, both for sharing their experience in the industry and their financial support.

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Figure 9
Resulting Layouts