Journal of Computational Design and Engineering 4 (2017) 318–329

Contents lists available at ScienceDirect

Journal of Computational Design and Engineering

journal homepage: www.elsevier.com/locate/jcde

A computer-generated plus-shaped arrangement and its architectural applications

Krishnendra Shekhawat

BITS, Pilani Department of Mathematics, Pilani Campus, India

ARTICLE INFO

Article history:
Received 7 December 2016
Received in revised form 22 May 2017
Accepted 24 May 2017
Available online 1 June 2017

Keywords:
Adjacency
Algorithm
Architectural design
Arrangement
Rectangles

ABSTRACT

This work consider the problem of rectilinear arrangement which is about arranging given rectangular objects of different sizes in the frame of a given rectilinear polygon while considering dimension and position of each rectangle and adjacency relations among the rectangles.

The current work is part of a larger work aimed at automated generation of rectilinear arrangements while satisfying given dimensional and topological constraints. In this paper, we present a set of algorithms for obtaining a plus-shaped arrangement. In addition, we present some heuristic techniques for reducing the size of extra spaces present inside the obtained arrangement. At the end, we demonstrate architectural application of the presented work.

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1. Aims and significance

1.1. Motivation

The present work discusses a problem in constructive geometry which was initially presented by architects. This problem, which concerns the allocation of living spaces in a building, was the theme of a research project 'Formalisation et sens du projet architectural' (Pellegrino et al., 2008) where the objective was to develop a formalization of the architectural conception and to offer a computer-aided system of inference appropriate to the architectural process of composition. This research relates to the articulation between the sciences of architecture, semiotics of space, mathematics, and computing. The problem (in one of its forms) can be stated as follows:

Given a list of rooms and a weighted adjacency matrix (which defines the relative weights of the desired proximities among the rooms), all spaces must be enclosed within the shape of a cross made up of five rectangles. The constraints for allocation are that each arm of the cross must have at least one terrace and each room should be in contact with the outside world directly or through a terrace.

This problem has rarely been attacked by mathematical methods. Therefore, we tried to generalize this problem and applied a mathematical approach to solve it.

1.2. Introduction and related work

Combinatorics is the study of arrangements: pairings and groupings, rankings and orderings, selections and allocations and *constructive combinatorics* is the design and study of algorithms for creating arrangements with special properties (Harris, Hirst, & Mossinghoff, 2008). Thus, an *arrangement* of rectangular objects can be viewed as a branch of constructive combinatorics that is fueled by problems and applications from many fields of study.

The act of an *arrangement* of a set of objects has three essential components, i.e., the *geometry (position)* and *topology (similarity)* and *dimension* of the objects. In other words, it can be easily observed that in an arrangement, the elements having similar shape, reaction, function, orientation or direction are often grouped together while considering their position and dimension. Some interesting and well known examples of geometric arrangements are furniture organized in the most functional way, the famous Rubik Cube, or the arrangement of squares in the golden rectangle. Similarly, examples of topological arrangements are graphs that are grouped together if they have some common mathematical properties (planar graphs, bipartite graphs, etc.), periodic table where noble gases are arranged together on the basis of the chemical properties they share, etc.

In literature, many researchers have worked over the problem of arrangement of given objects within a predefined contour shape. Few of the relevant work is listed below.

Peer review under responsibility of Society for Computational Design and Engineering.
E-mail address: krishnendra.iitd@gmail.com

http://dx.doi.org/10.1016/j.jcde.2017.05.003
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In 1925, Moroń (1925) gave the first example of the dissection[1] of a 32×33 rectangle into 9 unequal squares. Then in 1940, Brooks, Smith, Stone, and Tutte (1940) obtained a perfect squared rectangle till order 13 using an electrical network consisting of currents, voltages, and resistance. It was C.J. Bouwkamp who first became interested in the problem of perfect squared rectangles during the early 1940s. Besides Bouwkamp and Duijvestijn (1992) also discovered the very first simple perfect squared square making use of computers in March 1978. It has the lowest possible order, $n = 21$, and it is the only one of that order.

In the above problems, the dimension of the rectangles evolves according to the need of the problem. If the dimension and the number of rectangles are given, then the relevant problems are known as packing problems. Rectangle packing problems aims at allocating a set of rectangular items to larger rectangular standardized units by minimizing the waste. In 2-dimensional bin packing problems, these units are finite rectangles, and the objective is to pack all the items into the minimum number of units, while in 2-dimensional strip packing problems there is a single standardized unit of given width, and the objective is to pack all the items within the minimum height (Lodi, Martello, & Monaci, 2002). For some of the recent works related to packing problems, refer to (Bortfeldt, 2006; Cui, Yang, Cheng, & Song, 2008; Cui, Yang, & Chen, 2013; Huang & Korf, 2012; Wei, Zhang, & Chen, 2009).

It is clear from above discussion that the packing and tiling problems are restricted to dimensional constraints only. In this paper, we are interested in both dimensional and topological constraints. Hence, we move to the *space allocation problem* which is about the computational arrangement of rooms (spaces) in a floor plan. Throughout the literature, many researchers have worked over the automated generation of architectural floor plans using algorithmic graph-theoretical approaches. This approach was first presented by Levin (1964) where a method was proposed for converting the graph into a spatial layout. In 1970, Teague (1970) represented the rectangular spaces by arcs in a network. Then in 1980, Baybars and Eastman (1980) demonstrated a systematic procedure for obtaining an architectural arrangement (not necessarily rectangular) from a given underlying maximal planar graph. In 1982, Baybars (1982) presented methods of enumerating the circulation spaces within a floor plan, as well as methods of constructing floor plans with circulation spaces. In 1987, Rinsma (1987) illustrated that for any given maximal outerplanar graph with at most four vertices of degree 2, it is not always possible to find a rectangular floorplan satisfying adjacency and area conditions. In 1997, Irvine and Rinsma-Melchert (1997) presented a graph-theoretical approach for generating orthogonal layouts. In 2004, Kalay (2004) talked about two approaches for solving this problem, namely, an additive approach and a permutation approach (for details, refer to March & Steadman, 1971).

As a recent work in this direction, in 2011, Alvarez, Río, Recuero, and Romero (2011) developed a tool for automatic drawing of two dimensional floor plans. In 2012, Regateiro, Bento, and Dias (2012) proposed an approach called orthogonal compartment placement based on topological algebras and constraint satisfaction techniques. In this work, the authors have proposed 169 ways in which two rectangles or rooms can be adjacent, which gives a new scale to the problem of defining the adjacency relations among the rooms. In 2013, Kotulski and Strug (2013) used a particular class of graphs, called hypergraphs, as a means of representing building layouts. In 2017, Ham and Lee (2017) presented an algorithmic approach for quantitatively evaluating structural similarities between architectural plans and creating a phylogenetic tree of the analyzed architectural plans.

In most of the above mentioned work, the output is restricted to rectangular arrangements only. Only, in a few cases, orthogonal arrangements are constructed from a particular class of graphs, namely, maximal planar graphs (Irvine & Rinsma-Melchert, 1997). Other than that, in a few approaches, the shape of the layout get evolved which is non-rectangular (Baybars & Eastman, 1980). Also, either the adjacency constraints are not considered or they are given by graphs. Clearly, in this case, it is difficult to introduce flexibility in adjacency relations among the given objects.

In this paper, we are considering the problem of packing of n given objects in a given specific dimensionless contour shape while satisfying given dimensional and topological constraints, where the topological constraints are given by a flow matrix (weighted adjacency matrix) (Jokar & Sangchooli, 2010), i.e., the adjacency requirement among the given objects are expressed in terms of weights and the dimensional constraints are given in terms of area (length and height) of given objects. In other words, the problem is to pack n given objects while satisfying given constraints such that the final shape of the packing should be similar to the given specific rectilinear frame. The work done is a part of a larger work aimed at automated generation of rectilinear arrangements while satisfying given dimensional and topological constraints. In this paper, as a way of illustration, we present a set of algorithms for obtaining a plus-shaped arrangement for given objects, although other shape arrangements could also be constructed.

For smooth reading of further text, here is the list of notations that are frequently used in the paper:

n: number of given rectangular objects,
R_i : i^{th} object,
ℓ_i and h_i: length and height of R_i,
$R^A(n)$: a rectangular arrangement with n objects,
$R^A_S(n)$: a spiral-based rectangular arrangement with n objects,
L_i and H_i: length and height of a $R^A_S(i)$,
$P^A_S(n)$: a spiral-based plus-shaped arrangement with n objects.

1.3. Example

For better understanding of the problem and its solution, to be discussed in this paper, let us consider the following example.

Example 1. Suppose we have given 16 objects, represented by $R_i, i = 1, 2, \ldots, 16$. The problem is to allocate the given objects, while satisfying given dimensional and topological constraints, in such a way that the final arrangement of objects should be a shape similar to the "plus-shape" shown in Fig. 1A. The dimensional constraints are given by Table 1 and topological constraints are given by a weighted adjacency matrix as shown in Table 2. A plus-shaped arrangement corresponding to Tables 1 and 2 is demonstrated in Fig. 2 where green rectangles are extra spaces. The steps involved in the construction of a plus-shaped arrangement are as follows:

1. Architecturally, a plus-shaped polygon can be seen as a building with five different wings, as shown in Fig. 1B, where it is partitioned into five rectangular zones (mathematically, idea is to partition given polygon into maximum number of rectangular zones in such a way that each zone should consists of at least 3 corners of given polygon). Hence, the next step is to look for the objects of each rectangular zone.
2. The objects of each zone are derived from given weighted adjacency matrix using an algorithm to be presented in Section 2.2. The objects belonging to each zone are as follows:

[1] *Rectangular dissection* is concerned with the division of a large rectangle into smaller rectangular pieces. A rectangle which is dissected into squares, all of which having different sizes (areas) is called *perfect*.

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