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Optimal design of plant lighting system by genetic algorithms

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Abstract

A genetic algorithm technique is developed for the optimal design of a supplemental lighting system for greenhouse crop production. The approach uses the evolutionary parallel search capabilities of genetic algorithms to design the pattern layout of the lamps (luminaires), their mounting heights and their wattages. The total number and the exact positions of luminaires are not predefined (even though possible positions lay on a fixed grid layout), thus the genetic algorithm system has a large degree of freedom in the designing process. The possibilities of mounting heights and luminaire wattages are limited to four different values for each luminaire in this study. A fitness function for the genetic algorithm was developed, taking into account light uniformity, light intensity capability, shading effects of the design, as well as operational and investment costs. The systems designed by the genetic algorithm show improved values of light uniformity and substantial savings without any effect on the light capacity capabilities of the system. Innovative automatically designed systems compare favorably with typical and expert-designed lighting systems.

Keywords: Genetic algorithms; Greenhouse; Supplemental lighting; Lighting system design; Optimal design

1. Introduction

One of the major parameters that influences plant growth is the availability of light. Greenhouse plant production systems have the capability of providing supplemental lighting during plant growth in cases where daylight is insufficient for optimal crop production. Supplemental lighting is provided to increase photosynthesis in plants and is often referred to as "assimilative lighting" because its main purpose is to increase the growth, that is, the assimilation of CO_2 in the crop (Ciolkosz et al., 2001). The effects of supplemental lighting on plant growth have been studied extensively (Austin and Edrich, 1974; Clarke and Devine, 1984; Wheeler et al., 1991) and the results have been applied to either light control (Heuvelink and Challa, 1989; Carrier et al., 1994; Albright et al., 2000) or a combination of light and CO_2 concentration control (Fierro et al., 1994; Both et al., 1998; Ferentinos et al., 2000; Ayari et al., 2000), as these two parameters are highly bounded in their influence on the plant growth.

Supplemental lighting in greenhouse facilities is provided by specially designed lighting systems, which, in the case of assimilative lighting (as opposed to morphogenic lighting where light is provided to control the plant form and not growth), usually consist of high intensity discharge lamps in direct reflectors, mounted in a grid pattern above the plants. The performance of these systems is measured in terms of uniformity of the light supplied and average light intensity provided (Deitzer et al., 1994). These properties are inherent of the design characteristics of the lighting system, the goal of which is to provide a highly uniform light level over the entire growing area in order to facilitate uniform crop production (Ciolkosz et al., 2001).

The structure and operating conditions of greenhouse plant production facilities make design of supplemental

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lighting systems a complex process. Many interactions exist between lighting systems and plants, such as photosynthesis, photomorphogenesis and thermal effects, and between lighting systems and parts of the greenhouse structure (e.g. reflections of the cover) and mechanisms of the production system (e.g. shading by other mechanisms). In addition, design properties of the lighting system are limited by several factors of the greenhouse production system, like the type of cultivated plant, greenhouse layout, available greenhouse height, desired light intensity level, light distribution of the luminaires and their power consumption, and the availability of electric power. Electrical efficiency of the lighting system is the most important parameter in the majority of studies in system design (Sager, 1984; Bubbenheim et al., 1988; Albright and Both, 1994; Both et al., 1997). A more detailed study by Ciolkosz et al. (2001) gave some useful results on the effects of luminaire selection and layout on the level of uniformity of the provided light of supplemental lighting systems. In addition, a decision model was developed for the appropriate lighting system selection for specific plant growth scenarios, based on expert inputs and performance calculations (Ciolkosz et al., 2002).

The limited extent of works on lighting system design for greenhouse plant cultivation systems is mostly due to the complexity of the process and the lack of a design tool that can be applied to specific greenhouse structures with known requirements concerning the cultivation of specific plants. In this work, a goal-oriented design approach is proposed, based on the evolutionary optimization properties of genetic algorithms (GAs) (Holland, 1975). In goal-oriented design, an algorithm is used to search the design solution space looking for high performance solutions in terms of specified goals (Caldas and Norford, 2002). GAs have been used in design engineering applications (Jenkins, 1991; Renner and Ekart, 2003), mostly in the area of construction design, such as optimization of structural design (Hajela and Lee, 1995; Camp et al., 1998; Raich and Ghaboussi, 2000; Nanakorn and Meesomklin, 2001; Chou and Ghaboussi, 2001; Ali et al., 2003), automated design of steel frames (Koumousis and Georgiou, 1994; Foley and Schinler, 2003; Saka, 2003) or concrete frames (Rajeev and Krishnamoorthy, 1998; Camp et al., 2003) and optimal spacing of grillage systems (Saka et al., 2000). In the majority of these applications, common forms of GAs have been used. An interesting modification of the algorithm was introduced by Raich and Ghaboussi (2000), namely the implicit redundant genetic algorithm, where a representation that included redundant genes in the chromosome of the algorithm was used to allow the freedom of having variable number of elements in the encoding of the GA. The design problem considered in the work presented here, sets an upper limit in the number of available elements (i.e., luminaires), thus a different representation approach was used, which was incorporated in a traditional binary encoding scheme of GAs.

2. Materials and methods

2.1. Lighting system

The design problem concerns the development of a lighting system for the supply of artificial lighting in a greenhouse plant production facility. The main design issues in such a system are the layout pattern of luminaires, their wattages and their mounting heights. Philips high-pressure sodium (HPS) luminaires of type PL90M were used in a simulation model, with the availability of four different lamp wattages: 250, 400, 600 and 1000 W. The possible positions for the placement of the luminaires were considered to be arranged on a squared grid with square dimensions 1 m × 1 m and total dimensions of 11 m × 6 m (Fig. 1). This grid was called the "luminaire positions grid". The growing area was the area defined by the luminaire positions grid expanded by 2 m on each side (Fig. 1), measuring a total area of 150 m^2. The common practice in lighting systems design is that all luminaires have the same mounting height. However, the genetic algorithm system developed here allowed the freedom of having different mounting heights for each single luminaire, with the ability of heights of 2.5, 3, 3.5 and 4 m from the level of the crop. Different mounting height of luminaires in a layout is essential because it can be a way to balance the effect of having greater light intensity

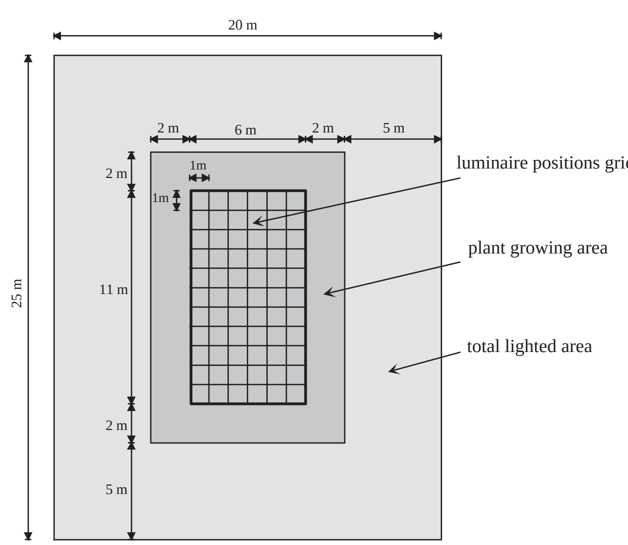

Fig. 1. Schematic representation of the positions grid of the luminaires, the plant growing area and the total area that can be illuminated by the lighting system.