Multi-objective mixed-integer evolutionary algorithms for building spatial design

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Chapter 1

Introduction

1.1 Background

Darwin's description of the origin of species has not only revolutionised the field of biology, but also influenced many other disciplines. It even affected the most unexpected of fields, computer science. The relation between nature and computational machine may not be intuitive, but is certainly clear upon closer inspection. In nature, evolution is able to find the most extraordinary solutions to the problem of survival, in an unimaginably large set of possible solutions. Computers are tasked with quite similar challenges in optimisation problems. As such, researchers envisioned algorithms using the same process of evolution to find solutions to whatever problems are presented to our computers.

This mimicry of nature has proven to be a tremendously successful tool in exploring many alternative solutions, finding optimal solutions, or presenting the possible trade-offs between solutions. Yet, many challenges remain in the field of evolutionary optimisation. How can constraints be handled? How to optimise with multiple objectives in mind? How to handle mixed-variable search spaces? Although research is progressing in each of these areas, this work takes a step further by investigating the combination of the three: constraint handling, multi-objective optimisation, and mixed-variable optimisation.

As a starting point this combination is focused on the domain of the built environment. After all, what better place is there to challenge these techniques, and take them beyond their current capacities, than in the real world? The built environment is considered as a practical application area for the algorithms to optimise the buildings where people spend so many a waking – and sleeping – hour. Construction and exploitation of these buildings is estimated to amount to 40 % of our resource expenditure [45], and presents an opportunity for massive savings. Savings in costs, material and immaterial, ultimately reducing the negative impact on our environment.

Here it is investigated how multi-objective evolutionary computing can improve building designs, particularly in the earliest phases of the design process. During these early stages decisions are made that largely restrict the options later in the process. Changes to this fundamental design at later stages would result in having to redo a significant part of the work, making it essential to find optimal designs early on.

More specifically, this thesis focuses on spatial design, a field where all the interests in improving evolutionary computation are met. Spatial design considers the shape of a building, and its spatial organisation. In this design it is essential to consider multiple objectives. It should be structurally sound, but also energy efficient. A design also has to be feasible. This is enforced by structural constraints, that – for instance – prevent designs with rooms floating in the sky from being considered. Describing these designs to a computer requires multiple variable types, resulting in a mixed-integer search space. The width of a room can be expressed by a real number, whereas the number of rooms is necessarily integer. To handle all these challenges, a constraint handling multi-objective mixed-integer evolutionary algorithm is developed in this thesis.

1.2 Research Questions

Improving multi-objective evolutionary computing, and applying it to spatial design optimisation is no straightforward process. To achieve this vision, the following research questions are considered in this thesis.

RQ1 (Chapter 3) How can elements of the solution space be represented?

To automate building spatial design optimisation, a computer understandable representation is a must. However, defining such a representation is not straightforward. A representation easily understood and modified by a human is often difficult to handle for a computer, and vice versa.

RQ2 (Chapters 4 and 5) How can the discovery of feasible designs be ensured?

Constraints arise from physical limits (buildings cannot float in the sky), but also from practical matters such as the limitations of a simulator. Ensuring no infeasible designs appear in a representation is challenging in itself, but can also conflict with ensuring all feasible designs can be represented. As such, the optimisation process must be able to navigate a search landscape limited by constraints, and be able to reach every feasible solution.

RQ3 (Chapter 6) How can local search contribute to the improvement of solutions found during global search in a multi-objective setting?

Identifying promising regions in the search space can be done efficiently through global search by evolutionary algorithms. Given time, they can also approach local optima. Assuming a relatively smooth surface however, traditional numerical methods may do so faster and more precisely. On the other hand, not many multi-objective numerical methods have been developed yet, and existing ones have only been evaluated on simple test problems. If these multi-objective numerical methods are applied successfully in local search, they may find better local optima.

RQ4 (Chapter 7) What can be learned about building spatial design from the optimisation process?

Optimisation processes produce large amounts of data about the problem they are tackling. This data provides an opportunity to learn about the optimisation problem, in this case building spatial design. By analysing the data, it may be possible to answer questions such as: What properties are intrinsic to an optimal building spatial design? How do optimal designs for different objectives compare? What heuristics can humans learn from the solutions found by algorithms?

RQ5 (Chapter 8) How can a generally applicable multi-objective mixed-integer algorithm be developed?

The case study of building spatial design is an illustrative example of how multi-objective mixed-integer optimisation can work. Unfortunately, algorithms specific to this problem will be inefficient, or may even not work at all, on other problems. Developing a general multi-objective mixed-integer algorithm is therefore an important next step.

RQ6 (Chapter 9) How applicable are the developed algorithms to real world problems?

Beyond the question of how the developed algorithms perform on the considered problem, it is important that they integrate well into the larger design process.

To this end, the interaction of the optimisation processes with existing design tools, and their human operators has to be investigated.

1.3 Terminology

Although this work primarily focuses on computer science aspects, there is a strong interaction with the field of the built environment. At the intersection of multiple disciplines it is important to clearly define the used terminology, in order to avoid confusion when using language common to both disciplines. For instance, *space* is used with different meanings in both fields. In computer science space commonly refers to the space of possibilities, such as the real numbers. Whereas in civil engineering space refers to a part of a building, such as a room, atrium, or hallway. To prevent this confusion, space is always preceded by an identifier when used in the computer science sense, e.g., real space, decision space, or objective space. While for civil engineering no identifier is used, e.g., the building has three spaces, or an elongated space is considered. Definitions for the large amount of technical terminology are provided in the glossary (page 183).

1.4 Notation

Per the international system of units (SI)[1] all unit names are written in lower case (e.g. kelvin, or kilogram), and unit symbols are also in lower case, except for the first letter when they are derived from a name (e.g. K, or kg).

1.5 Outline

Following on from this introduction, Chapter 2 provides the reader with background information on optimisation, multi-objective optimisation, evolutionary computation, and the basics of building spatial design. Chapter 3 then introduces a design space representation for the considered problem of building spatial design, as progressively developed over multiple published articles [16, 17, 21, 25], with the aim of answering RQ1. Furthermore, additional unpublished work is presented on alternatives and limitations of the described representation. In Chapter 4 the objectives for building spatial design are considered as individual optimisation objectives, as previously published in

[1] https://www.bipm.org/utils/common/pdf/si-brochure/SI-Brochure-9-EN.pdf

[17]. In addition, basic constraint handling with penalty functions is investigated, which is related to RQ2. Chapter 5 continues to look at constraint handling (still RQ2), but now for the multi-objective case of building spatial design, as published in [15, 16]. Since penalty based constraint handling proved to be of limited use, problem specific operators, that do not violate the constraints, are developed. Furthermore, the chapter employs landscape analysis to improve the understanding of the problem, as well as parameter tuning to maximise algorithm performance. In Chapter 6 the previously introduced problem specific multi-objective algorithm is combined with local search as published in [19] in order to answer RQ3. The optimisation data produced during the local search study is analysed in Chapter 7 (RQ4). Here, the aim is to extract design rules from the data in order to verify that the resulting spatial designs are sensible solutions, as published in [18]. Moving forward from specialised algorithms, Chapter 8 pertains to RQ5 and considers general multi-objective mixed-integer optimisation with evolution strategies, which has been published in [20]. Chapter 9 then looks at various applications of the introduced optimisation techniques for building structural and building spatial design [21, 22, 23, 24, 25], which answers RQ6. The thesis is then concluded in Chapter 10 with a discussion of the achieved results, answers to the posed research questions, and interesting directions for future studies relevant to this work.

1.6 Contributions of this Thesis

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1.7 Other Work by the Author

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