Integrated Spatial-Structural Optimization in the Conceptual Design Stage of Project

A tool to generate and optimize design solutions aiding informed decision making for Architects, Engineers and Stakeholders

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Healthcare design projects require the careful integration of spatial and structural requirements. Today, design teams typically resolve these requirements in two separate, largely sequential steps. In the first step, architects leverage their experience and vision to develop space plans that address program and goals. Next, based on the architect's recommended design, engineers generate and refine a structural design to address structural requirements. This manual process produces a very limited number of non optimal spatial and structural design solutions with unclear decision rationale. This paper presents the Integrated Spatial-Structural Optimization (ISSO) decision making methodology. ISSO supports design teams by helping them generate, analyze, and manage a vast number of integrated spatial and structural solutions. ISSO features a bi-level optimization workflow that has been customized for spatial and structural design of healthcare facilities. The paper describes implementation in the Dynamo parametric modeling platform, and retrospective validation of the algorithm and workflow on an industry case study to demonstrate how ISSO can help design teams generate, analyze, and manage more conceptual design options.

Keywords: *Spatial Design, Generative Design, Design Optimization, Facility Planning, Design Tools, Design Automation*

INTRODUCTION

Facility layout problems, found in design domains including circuit boards, service centers, airports, and hospital, seek to locate and interrelate objects to optimally meet requirements (Yeh 2006, Singh and Sharma 2005, Drira et al. 2007). For instance, to design the layout of a hospital, designers must interrelate various organizational units (e.g. pharmacy, lab, patient room) to satisfy design requirements and minimize resource consumption (e.g. nurse travel time). Also known as space layout problem in building design, facility layout problems are NP-hard problems requiring heuristics to manage the vast design spaces. Healthcare facilities are extreme examples because they have extreme spatial complexities wherein multiple operational variables are in process to satisfy the design requirements of many stakeholders. The challenge is how to structure a design process that allows the stakeholders most systematically explore the design process to maximize stakeholder value (Clevenger et al. 2013).

In hospital design, Hassan et al. (2014) explored heuristic methods including hill climbing, simulated annealing, and extended simulated annealing with genetic algorithm-style operators to model pedestrian flow statistics and find feasible spatial layout design elements. Using exact methods such as Newton's differential equation, Lorenz et al. (2015) improved the change management aspect of hospital layouts design by propagating local changes immediately to the global space layout. However, most space layout planning studies focus on single-objective optimization, which are limited in practice. For example, a hospital layout that is optimized for space allocation may not have a feasible or affordable structural layout. Holst et al. (2013) suggests that researchers should solve the space layout problem of hospitals as a multi-objective optimization problem, where various parties may have conflicting objectives. To this end, the objective of this study is to develop an integrated spatial-structural optimization (ISSO) approach to incorporate parametric structural design into space layout designs of hospitals at the conceptual design stage.

STATE OF THE KNOWLEDGE AND PRACTICE

Hospitals have highly complex layout constraints and requirements, making their design one of the most critical facility layout problems. While architects are typically responsible for aesthetic and effective spatial designs, structural engineers focus on the structural functionalities of these layouts. Due to time constraint and lack of structural consultants in the team in conceptual design stage, architects often create designs based on architectural contexts and requirements without explicitly considering structural constraints and requirements. Next, structural engineers develop structural designs based on the architectural design recommendations (Clevenger et al. 2013, Hassan et al. 2014). Because of the separation in workflows and goals, finding solutions that optimize both architectural and structural requirements of a project is challenging. Thus, project teams may benefit from a tool that automatically generates and analyzes initial structural configurations (e.g. the placement of columns) based on proposed spatial design or schematic layout in the conceptual design stage (Mora et al. 2006), and helps them understand trade-offs, and communicate preferences and a common decision between architects and engineers.

Reference	Spatial Optimization	Structural Optimization	Hospital Design	Decision Making
Elshafei (1977)	Yes	No	Yes	No
Vos et al. (2007)	Yes	No	Yes	No
Nimtawat & Nanakorn (2009)	No	Yes	No	No
Mora et al. (2006)	Yes	Yes	No	No
Delgado and Hofmeyer (2013)	Yes	Yes	No	No
ISSO	Yes	Yes	Yes	Yes

Table 1
Summary of the studies on structural/spatial design problem.

Reflecting the lack of integration between architectural and structural design, most of the studies in literature only focus on one or the other problem in hospital design (Table 1). For instance, Elshafei (1977) formulated a hospital layout as a quadratic assignment problem to minimize the effort of patients walking from one department to another. Vos et al. (2007) evaluated the flexibility and fit of an architectural design for the operation of a hospital. Hahn et al. (2010) proposed a method that generate the design of the departments of a multi-story hospital design while accounting for the evacuation plan of patients. Helber et al. (2016) proposed a hierarchical planning approach, for large and com-

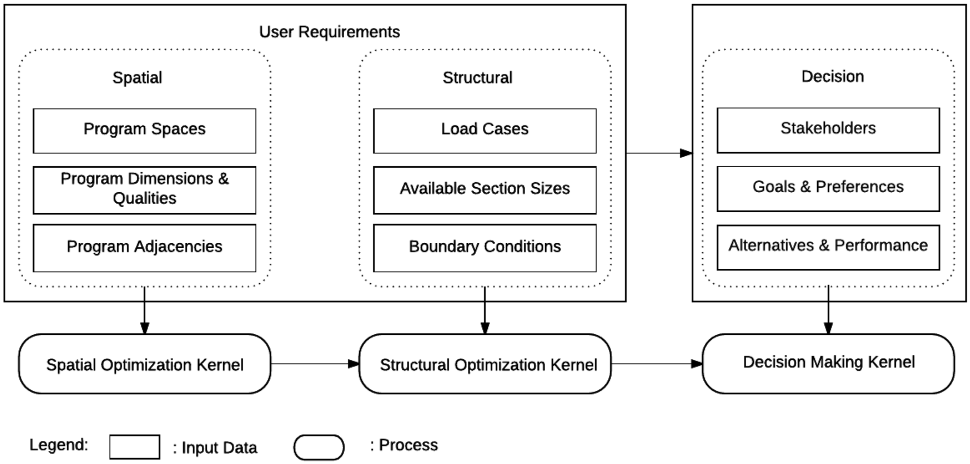


Figure 1
Overview of the research methodology.

plex datasets, to calculate the location of departments and wards. To solve the structural and spatial optimization problem in non-healthcare projects, Nimtawat and Nanakorn (2009) employed a grid-based topology optimization method that automatically generates beam-slab layouts. Mora et al. (2006) developed a prototype called StAr which enables engineers to find the best solutions from architectural and structural designs. Delgado and Hofmeyer (2013) proposed a virtual toolbox that generates optimized structural design solutions from spatial designs through simulating the iterative interaction between spatial and structural designs. However, their current implemented model only generates structural layouts for spatial designs without optimizing its structural layout.

A major limitation of these studies is the lack of an integrated environment for establishing parametric relations and dependency among architectural and structural elements for design generation, analysis, and decision making. This study aims to develop ISSO, an integrated spatial-structural optimization toolkit to help designers during the conceptual design stage to explore more design alternatives before choosing optimal solutions. ISSO provides an interface and process to bring architects, engineers, and stakeholders together early on in the project cycle, imparting the opportunity to define shared objectives and generate spatially and structurally promising design solutions, understand the tradeoffs, and make and communicate better-informed decisions.

METHODOLOGY

ISSO has four main phases (Figure 1). First, users define their spatial-structural requirements such as list of program spaces, adjacencies, qualities, load cases, and section types. Next, the spatial optimization kernel optimizes the space layout problem, based on the spatial requirements. Third, these spatial layouts are optimized using structural optimization kernel. Finally, users construct pareto-optimal solutions and then select optimum solutions based on decision theory and social network techniques. The following sections describe the details of the process.

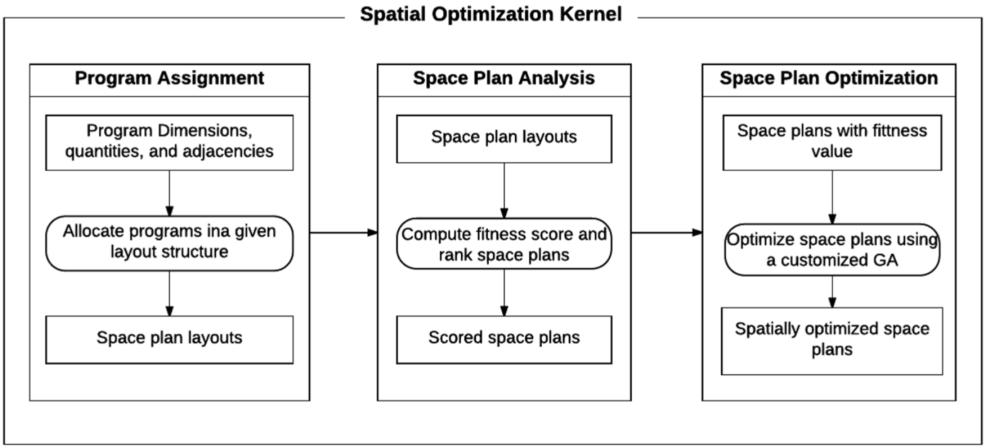


Figure 2
Higher level process map of the Spatial Optimization Kernel.

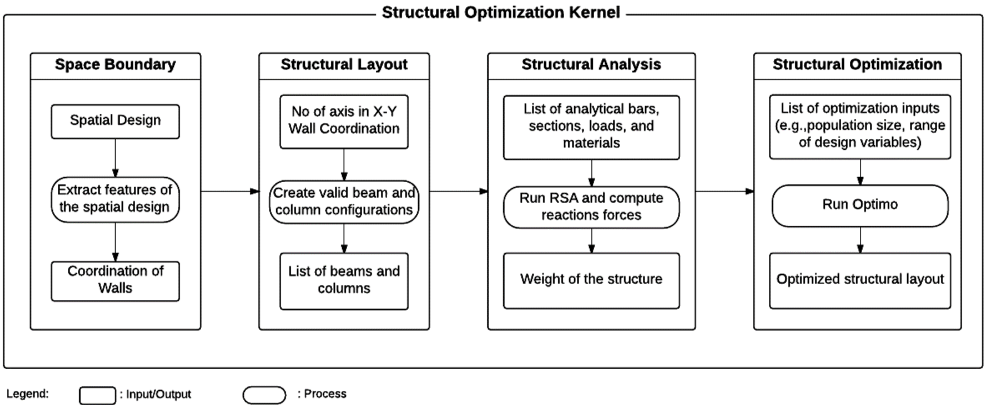


Figure 3
Design process of parametric structural design optimization.

User Requirements
First, project design teams (including architects and engineers) input contextual data into the system, including template layouts as shown in Figure 4(a). They represent layouts from industry best practices, constraining spatial allocation of program elements to industry tested layouts. Next, architects input facility program data, including program names, quantity, area, dimension or spatial aspect ratio expectation, as well as priority values for each program element, on a scale of one to 10. For example, an exam room is likely to be more relevant for the design team than staff toilet. After completing the spatial requirements, users input structural analysis data such as building materials, a list of sections, and loads and supports.

Spatial Optimization Kernel
The first stage of ISSO seeks to quickly generate and analyze spatial design alternatives (Figure 2). To begin, the architect develops a building program, consisting of a list of spaces, their required dimen-

sions, and adjacencies. Next, the architectural designer creates any number of template layouts that represent common and successfully accepted layout

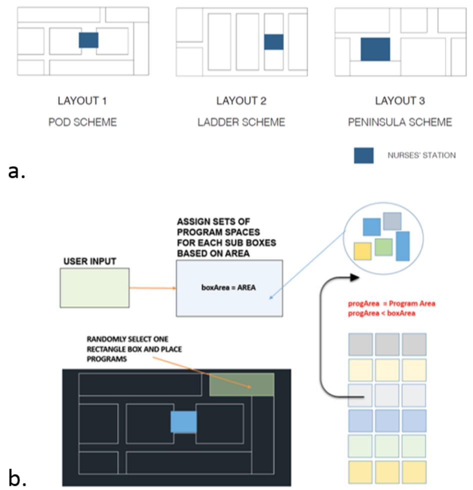


Figure 4
(a) Test case template layouts for the exam room department (b) Sub-list making process of program spaces.

ISSO uses a custom Genetic Algorithm (GA) to automatically pack rectilinear spaces onto these template layouts in order to generate and evaluate hundreds of alternatives against design goals and objectives in the form of a fitness function. The algorithm packs programs in a wide range of ways to create distinct individuals in the initial population, then randomly selects one of the rectangles and starts to prepare sub-lists of program spaces as shown in Figure 4(b). First ISSO parses template layout provided and builds a list of empty rectangle boxes. In every iteration, ISSO randomly selects an empty rectangle box and starts assigning programs to it. The system keeps a check on the total area of selected program spaces, which should not be more than the selected empty rectangle box. If the area exceeds, then the program quits this rectangle and moves on to the next rectangle box and this goes until all rectangles are selected. At the next step, in order to pack the program spaces inside the rectangles, the code iterates through each of the rectangle boxes and selects its sub-list of program spaces. The algorithm places the input program spaces on one of the rectangle boxes (selected randomly) by aligning its shorter edge with the shorter edge of the bigger rectangle box (Figure 7(a)). This process is repeated till all the input rectangle boxes are packed or till there is no more space available in the rectangle boxes. The algorithm then computes a fitness function based on adjacency between relevant spaces & leftover waste space to score and rank each alternative. The GA learns from the fitness score after each round and steers the future alternatives to deliver better design alternatives. Figure 5 describes the Spatial Optimization Component in more detail.

Structural Optimization Kernel

The second stage of ISSO integrates a parametric structural optimization process that automatically generates structural layouts satisfying structural re-

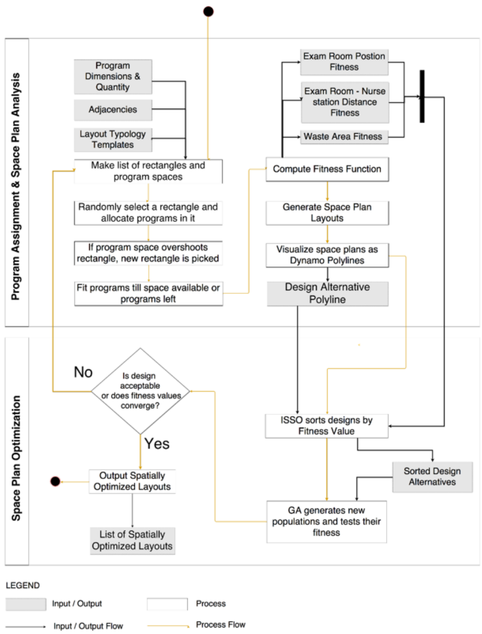


Figure 5
Process Map showing the Spatial Optimization component of ISSO.

quirements by considering space boundaries and requirements established in the first stage. Figure 3 shows the workflow of the parametric structural design optimization, including four phases: space boundary, structural layout, structural analysis, and optimization.

Space Boundary: An algorithm developed in a Python script node extracts details required for implementing structural analysis such as coordination of each corner of rooms, from spatial design alternatives (Figure 8(b)). Output of the algorithm is the boundaries of spaces in which structural elements will be placed next. The algorithm also determines whether a wall is along EW or NS directions.

Structural Layout: The inputs from Optimo, a Genetic Algorithm based optimizer in Autodesk Dynamo (Asl et al. 2015), identifies the number of axis in EW and NS directions as well as profile sections of beams and columns. Then the algorithm checks if there is any wall within a determined distance which is 0.1m to 1.5m here from an axis. If there is any wall within this distance, the algorithm measures the total length of walls located at the same distance from the axis and finds the location of the maximum total length so as to move the axis to that location. After placing axes, the algorithm places columns at each intersection of axes, except those intersections that fall within corridors or spaces. In addition, the algorithm places beam between each two columns along each axis.

Structural Analysis: In this step one of the node in Dynamo, part of SAP package assigns analytical bars, structural loads, materials, profile sections, and supports to the model generated in the previous step. After that, one of the nodes in SAP transfers values to Robot Structural Analysis for calculating and analyzing the maximum and minimum stresses and structural weights. If the stress of a member to the maximum allowable stress is more than one, then the design will be automatically rejected.

Optimization: ISSO is based on discrete optimization; however, since Optimo generates continues real inputs, a Structural-Optimization custom node has been developed to round real values to integer, adopted from Asl et al. (2015). For example, if a generated value in Optimo for number-of-axis is 4.3, then the Structural-Optimization custom node will round the value to the closest integer number which is 4 in this case. Optimo will keep track of inputs and outputs until finding variables that generate solutions with an acceptable stress ratio and less structural weights (Figure 9). Then designers can compare structural details of the potential space design alternatives to select the best spatial design alternatives that satisfies requirements of both spatial and conceptual structural designs.

Decision Making Kernel

The final stage of ISSO seeks to bring the spatial and structural design spaces together into an integrated framework for decision making. After generating a design space of promising alternatives, the design team is able to use a variety of tools to analyze this data, understand trade-offs, and provide final preference weighting to communicate a decision. For analyzing the tradeoffs a number of free tools are becoming available. Ultimately the resolution of these tradeoffs requires knowledge of the preferences of the stakeholders. We, therefore, imported the data for the most promising alternatives into the Wecision decision making tool (2016). Multiple scoring and weighting schemes are possible in Wecision, Figure 10 shows the application of the "Choosing by Advantages" methodology, where stakeholders collectively determined the Importance of Advantages between Alternatives. Importance of each advantage is summed to determine the Alternative with the greatest Value.

The decision making kernel provides an interface to select options not only by gauging users objective and subjective design choices. For example, stakeholders can input on a scale of 0 to 100, between all the options, how effective they find the circulation design for the said option. They can input like or dislike reaction on a certain aspect of a design option. Subjective inputs are translated to

Figure 6
Higher level process flow of decision making kernel.

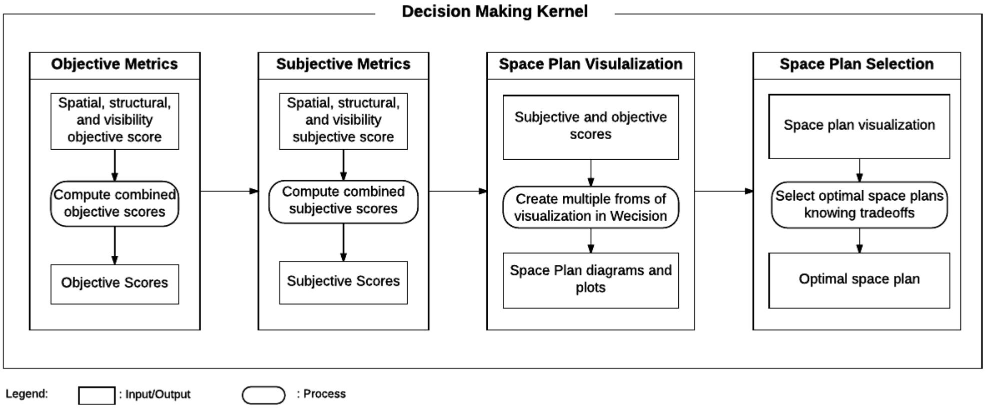
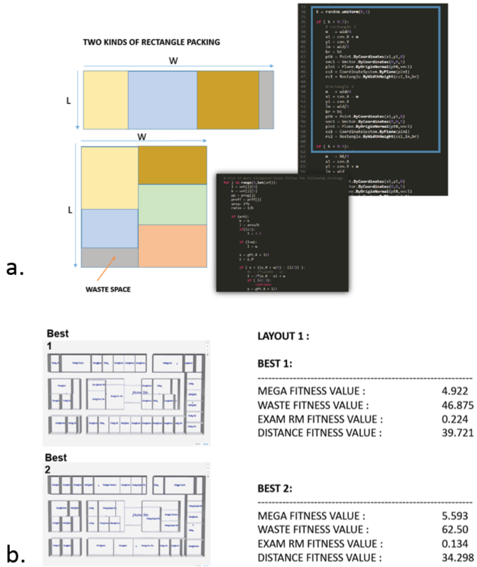


Figure 7
(a) ISSO, spatial optimization model showing different ways to place program elements in the input rectangle boxes. (b) ISSO - Output space plan layouts with individual scores and overall space plan scores.



quantitative values, then they are summed with objective inputs, then normalized and visualized in the interface. Wecision communicates each design options total performance and individual performance ratings against the set criteria, with respect to each other. This aids decision making by stakeholders as they are informed early on in the project cycle about the pros and cons of the design choices they make.

CASE STUDY - PROTON CENTER

We tested ISSO on a Proton Therapy Center, an existing project designed and built by an architectural practice in the USA. ISSO implemented and testified the process above to enable the design team to generate and explore a large number of potential alternatives as design solutions. We intended to have ISSO rapidly generate and evaluate large numbers of alternatives specifically focusing on the outpatient clinic department comprising of nurse station units and exam rooms. Table 2 describes the design space investigated in the case study.

Table 2
Details of spatial adjacency and structural layout optimizations.

Optimization	Spatial Adjacency	Structural Layout
Design Objective	Minimize distance from nurse station to the programs	Minimize structural weight
Design Variables	x,y coordinates of program blocks inside the domain space	Number of axis in EW direction (NEW)
		Number of axis in NS direction (NNS)
		Location of grids
	Length & breadth of program spaces	Column profiles
		Beam profiles
Constraints	Each program space should not be overlapping one another	No column in the middle of corridors or rooms
	Length & Breadth > 2.5m	Span length <= 7m
Design Variable Domains	0=< x =< length of bounding box	0< NEW <6, 0< NNS <6
	0 =< y =< breadth of bounding box	Profile sections of columns/ beams

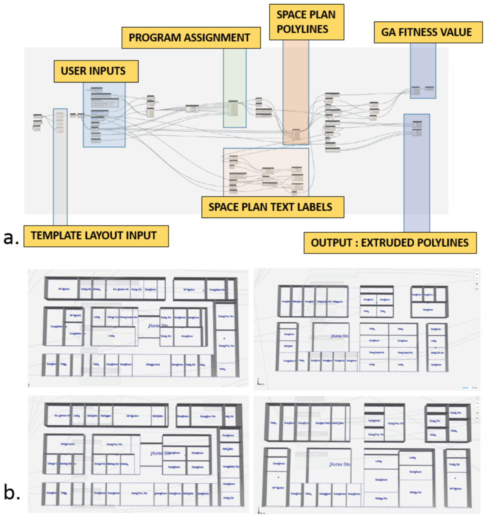


Figure 8
(a) ISSO - State of the Dynamo Graph generating spatially optimized space plan. (b) Set of labelled space plan options as output represented as polygons and poly surfaces depicting program elements.

Define user requirements

For this prototype, we investigated on three template layouts namely a pod, peninsula and ladder scheme. We evaluated the space plans with respect to the following metrics:

Adjacency factor - the spatial proximity of exam rooms to the nurse stations and the spatial togetherness of all exam rooms in the hospital. Lower value represents better fitness.

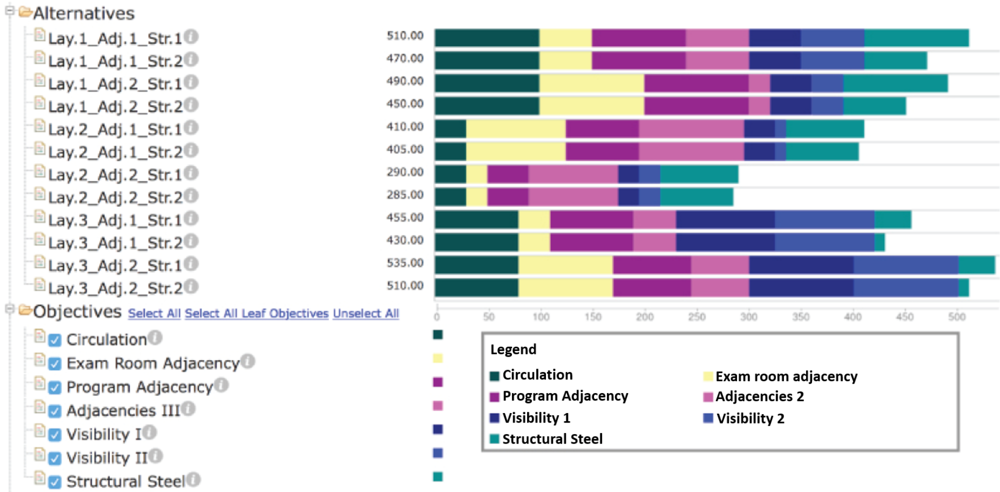
Structural factor - the weight of the structure, inferred by generating and analyzing beams and columns from the structural grid layout. Lower value represents higher structural fitness.

Visibility factor - the amount of visibility the nurse station gets for each spatial layout alternative generated. Higher value represented better space plan fitness.

Generate Spatial Layouts

After the design team defined the requirements, ISSO set about generating a design space of potential space plans, scored in terms of the metrics. ISSO commenced the process with an initial population of randomly generated spatial configurations. Next, it scored them for their ability to minimize the adjacency factor inclusive of distance between exam rooms, distance from nurse stations to exam rooms, and leftover wasted space (Figure 7(b)). The system (Figure 8(a)) sorted the spatial layouts based on the adjacency factor and prepared the next generation of the population. Further, the system produced a new generation by combining the best layouts from previous iterations with new spatial layouts that are generated randomly or cross-bred with two potential spatial layouts from previous iterations. This process iterated until the fitness values stabilized and generated potential design alternatives, as shown in Figure 8(b). In the last step, selected design alternatives passed on to the structural optimization kernel.

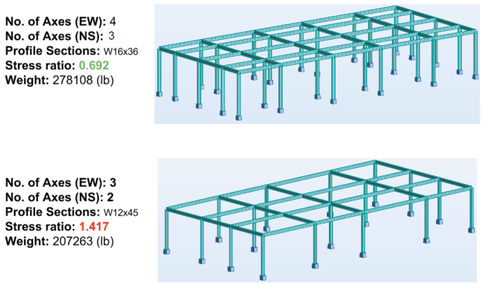
Figure 9
Visualization of various alternatives in Wecision, showing stakeholder preferences determining the winning solution, showing the tradeoffs of various options with respect to circulation, visibility, adjacency, structural weight etc.



Generate Structural Solutions

In the next step, for each spatial layout, the structural optimization kernel fit a grid of beams and columns. The optimization algorithm optimized the structural layout based on the number of axis on the X and Y direction, and the section of each structural member. Columns that were not placed on the walls were either moved or removed from the design. The structural optimization kernel minimized the weight of structural members while satisfying the yield stress requirements. Figure 9 shows the structural layout of three selected spatial design alternatives.

Figure 10
A set of structural design alternatives.



Make Decision

Finally, ISSO provides a collection of promising spatial and structural designs to the decision making kernel for final weighting and communication of the decision. Figure 10 shows the resulting designs, with their attributes and importance identified, and the importance of the advantages weighed by the decision maker.

DISCUSSION AND CONCLUSION

ISSO seeks to assist architects in a new type of design process - one in which they can simply input their design preferences, generate a broad variety of spatial and structural designs, and find the best design solution. We tested ISSO retrospectively on data from the design process for the Nurse Station & Exam room department for a cancer treatment facility. The description of the research process describes how ISSO renders a number of novel design alternatives that optimized either spatial goals or structural goals or a trade-off between both, which can inform designers of better design directions. The prototype test on the Proton Therapy case study successfully delivered multiple space plan options optimized for spatial adjacency and structural cost principally. It was successful to broaden the design team's overview of the design space at hand, with the specific score for each design. However, from the case study, we realized that the optimization processes adopted were agnostic of each other, limiting possibility to generate many more potential design options for the design team. Next, we look forward to implementing simultaneous multi-objective optimization of the processes described in ISSO to deliver robust and more realistic space plan layouts. ISSO highlights a workflow. Starting from existing template layouts, combining industry best practices with automated systems are one of the salient features of ISSO. In future, we envisage to develop ISSO develop its own template layouts.

Future experiments will test the extent to which ISSO can allow architectural designers to better support structural design requirements, decrease the number of design modifications during structural design stage, reduce waste space, optimize spatial layouts, structural layouts, initial dimensions of structural elements, and structural weight of many design alternatives. ISSO seeks to increase the spatial and structural performance of a design, decrease the cost and time of projects, and enhance collaboration between architects and structural engineers.

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