# ArDOT: A TOOL TO OPTIMISE ENVIRONMENTAL DESIGN OF BUILDINGS

Monjur Masum Mourshed, Denis Kelliher, and Marcus Keane
IRUSE (Informatics Research Unit for Sustainable Engineering)
Department of Civil & Environmental Engineering
National University of Ireland Cork, Ireland

## ABSTRACT

Environmental design of buildings involves 'finding the optimum' solution satisfying predefined objective(s) (e.g., reduction in operating/capital cost, maximisation of daylighting etc.). A number of computer based simulation models exist to assist professionals in finding this optimum through building performance assessment. Contemporary practices involving building simulation require enormous effort to prepare input, extract output, and visualize data, which restricts designers from realizing the full potentials offered. In most cases, rules of thumb are applied and experienced guesses are made; simulation software is used only to validate the assumptions, which do not necessarily lead to the intended optimum. Moreover, these tools have been developed as simulation engines, which is inadequate to visualize the compounded and interdependent effect of a large number of design variables.

The authors believe that to realize the potential offered by building simulation software, a new breed of DBSs (Decision Based Systems) is needed coupling existing simulation engines with formal optimisation methods through neutral data standards (BPM – building product models) for seamless integration. This paper first elaborates on the previous attempts at solving integration issues related to the design process and simulation; also attempts at finding the limitations. Secondly, formulation of design problems as optimisation has been discussed with reference to the different stages of design. Thirdly, for effective integration of activities among stakeholders and processes, the use of client/ server oriented building product model has been proposed to overcome the limitations of file-based prototypes. Analysis and discussions based on the above aspects form as justification for ArDOT, an Architectural Design Optimisation Tool under development at IRUSE, National University of Ireland, Cork. Combining all three aspects into one makes ArDOT unique, which is essentially an enhanced decision making tool for the design of energy efficient buildings.

## INTRODUCTION

Environmental design in architecture requires an integrated approach considering the domains of thermal, visual, and acoustic, which have effects on human comfort. Current generation of simulation software can be used to assess the environmental performance of the proposed building during design stages. They usually act on a single-view of the building as a system, be it thermal, visual, or acoustic. The use of such single-view tools for better and informed decision-making can be misleading. For example, increasing the glazing area in the south wall may increase the level of daylighting in interior spaces but leads to a significant increase in the heating/cooling load; thus requiring more energy to keep the space within comfort range. Simulation software, even the 'integrated' and 'whole building' ones are somewhat limited in modelling and representation of multi-domain complexities. Given the focused nature of development activities in building simulation community, some sort of decision-making tools are necessary combining single-view programs into one.

The emphasis of the development activities in building simulation has been to increase the domain-modelling capability. Little has been done to integrate with the design process, for which they have been intended. Attempts made at developing the 'design dashboard' type of applications adding a separate visualization front-end are not without limitations (Mourshed et al. 2003). Such attempts at integration of simulation engines and visualization front-ends can be found in Papamichael et al. (1997), Hand (1998), and de Wilde et al. (2002). The limitations are mainly in the domain of visualization and decision-making. For example, to study the combined effects of design variables in the daylighting problem (e.g., how energy cost varies for different values of window area) described earlier, designer needs to simulate the building changing the window area gradually (parametric runs) and checking the resultant daylighting level and heating/ cooling load. With the increase in the number ($n > 2$) of design variables, $(n+1)$ D design space (including the response) becomes hard to comprehend and visualize. As most of the design problems are n-dimensional (where, $n > 3$), authors argue that application of formal optimisation methods is the only way to search design space effectively.

Success of any design integration efforts depends mostly on effective communication between actors and stakeholders. Building product models are the natural replacement of cumbersome, stand-alone, and proprietary representation of buildings. Although building product models have been in existence for a number of years, their utilisation is still limited to the extraction of geometric information. Example can be found at Crawley et al. (2001) where IFC (Industrial Foundation Classes) have been used to convert geometric information from IFC to IDF (EnergyPlus Input File) format. This file based Import-Export activity is unilateral (IFC to IDF only) and not without problems especially in mapping of objects. For effective integration adhering to the principles of building product models, two-way communication in a client/server environment is essential. Manipulation of design variables from within CAD systems (which adheres strictly to IFC principles) can lead to better environmental design of buildings.

Prior to describing ArDOT, key environmental design activities with potential candidacy for optimisation need to be identified. Design goals or objectives also need special considerations, as they are usually conflicting in engineering design domains (Anderson 2001). The aim is not to eliminate intuitiveness in the design process but to supplement with analytical techniques, simulation software and optimisation methods. Previous attempts at design integration and optimisation in environmental design are described briefly followed by the considerations and the components that comprise ArDOT. The need for a single repository (building product model) to store building information is also established.

## INTEGRATING SIMULATION IN DESIGN

Building design is a sequential decision making process where information flow is mostly horizontal at the beginning. This implies that brainstorming of specialists and stakeholders is not efficient at early stages. Moreover, 'Composition of the design team, fragmentation of the process and activities make it unique from other mass-manufactured product design' (Mourshed et al. 2003). These factors together with unstructured data inadequate for detail oriented computer programs slow the uptake of simulation in early design activities. Even inclusion of specialists at the earliest is not feasible except for a few exemplary and large projects.

### Ongoing efforts

Design integration efforts can be classified into three depending on their approach. The first of these focuses on the interoperability issues, examples of which can found at Augenbroe (1995). Second category can be termed as 'process centric' definition of interfaces with adequate provisions for human expertise and judgement (de Wilde 2002). Emphasis was placed on the workflow between 'scenarios', 'tasks', and 'users'. 'Decision based' is the last category, where decision making plays a pivotal role in driving design and simulation activities. BDA (Building Design Advisor) is an example, which is based on the theories of design (Papamichael et al. 1997). Other approaches are not distinct to be categorized differently (Extensions designed to ESPr, Semper etc.).

To allow non-specialists (e.g., architects) to use simulation software a separate set of tools have been proposed and developed based on a simplified domain representation. In the course of time, they have been proved incapable to analyze the downstream impacts of alternatives. They are also inadequate to handle the increasing array of available information as design progresses.

Apart from differences in approaches, all the integration initiatives described above opted for a separate layer in the software architecture to deal with the decision-making aspect of design. Simulation engines are implemented and coupled merely to generate responses. A review of ongoing initiatives by Augenbroe (2002) also suggests the same. The authors argue that for successful integration, all three aspects need to be considered. Simply adopting 'process-centric' or 'decision-centric' approach or 'enhancing interoperability' would not solve the problems. A closer look at the implementations (DAI- Design Analysis Integration, BDA, etc.) shows that they only allow analysis of a specific scenario of design. Too much emphasis on one particular aspect sacrificed the flexibility in the other.

On top of the three approaches, optimisation methods need to be implemented for effective decision making in n-dimensional design spaces. Previous efforts on optimisation in environmental design are discussed later on in this paper, which shows that most implementations are AI (Artificial Intelligence) based, which are not the only types of algorithms. Experiments show that some of the gradient-based algorithms perform better in search of optimum environmental design.

## ENVIRONMENTAL DESIGN IN DIFFERENT STAGES

Being unaware of formal optimisation methods, AEC (Architecture, Engineering, and Construction) professionals strive to achieve optimality in designs through minimizing or maximizing certain predefined objectives. For each provisional design, the expected properties are predicted using simulation models, which are then compared to the requirements on the system. If the design does not meet the requirements, it is modified and evaluated again in the search for best possible design (Anderson 2001). The way to reach optimum is mostly experience based. Educated guesses are made to assume values of design variables and sometimes building simulation software is used to validate the expected performance. Moreover, the resolution of the domain knowledge increases as the design progresses and degree of responsibility varies among professionals as in figure 1. During early stages, architects are mostly responsible. 20% of the design decisions taken at this stage taken subsequently influence 80% of all design decisions. Apart from large-scale projects, energy consultants usually get involved at later and detailed stages, where most of the design decisions regarding building form, shape and elements are already made.

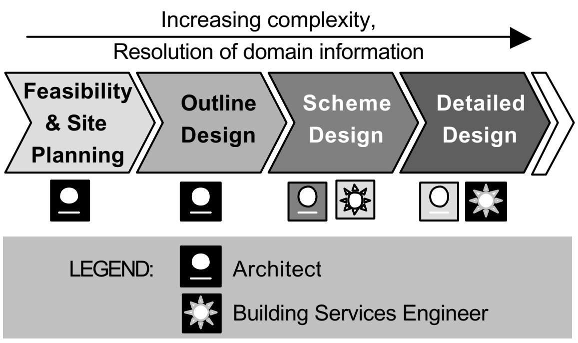


*Figure 1: Degree of responsibilities of professionals with respect to environmental design in different stages*

It has been argued by researchers for the provision of some decision support tools at early stages to bridge the gap. Optimisation techniques, a branch of decision support systems can be of help in this regard. The kind of problems in environmental design that can be solved using formal optimisation techniques are summarised in the following:

### Feasibility & Site Planning:

- Locating and approximate sizing of building,
- Studies on form, shape, and reciprocal cost of energy.

### Outline Design:

- Azimuth of the building (orientation with north),
- Shape and form of the building,
- Generic selection of materials based on transmission co-efficient,
- Architectural space programming and planning,
- Schematic elevation (% glazing area),
- Elementary appraisal of HVAC systems and fuel type.

### Scheme Design:

- Detailed Elevation and Massing Studies,
- Glazing area and type selection,
- Choice of shading device on different facades,
- Air change rate,
- Daylighting and overall lighting design,
- Selection of materials based on detailed analysis.

### Detailed Design

- Selection of heating/ cooling systems,
- Heating/ cooling control strategies and schedules,
- Detailed HVAC design including ductwork,
- Selection of ventilation strategies,
- Minor adjustment to shape, form, elevation, massing, materials.

## OPTIMISATION IN ENVIRONMENTAL DESIGN

Optimisation activity in environmental design usually involves minimizing certain objectives (usually the Cost of Energy or Life Cycle Cost) and sometimes maximizing others (maximize Glazing Area) based on user supplied constraints. Depending on the number objectives, it can be termed as single/ multiple objective optimisations. A minimization problem can be mathematically formulated as:

Minimize $f(x)$ (1.1)

Subject to $h_j(x) = 0, \quad j = 1,2,...n_h$ (1.2)

$g_k(x) < 0, \quad k = 1,2,..n_k$ (1.3)

$x_i^l \le x_i \le x_i^u, \quad i = 1,2,...n,$ (1.4)

Where, $f(x)$ is the objective function; $x = x_1, x_x, ..., x_n$ are design variables; $n_h$ is the number of equality constraints; $n_k$ is the number of inequality constraints; $n$ is the number of design variables; $x_i^l$ and $x_i^u$ are lower and upper bounds on a design variable, $x_i$. (1.1) represents objective function; (1.2) and (1.3) represents equality and inequality constraints respectively. (1.4) represents lower and upper bounds on design variables.

### Previous work

Applications of optimisation techniques in thermal design of buildings include but not limited to optimisation of building thermal envelope, HVAC system, and control. Al-Homoud (1997) used direct search optimisation technique to optimize building envelope consisting of up to 14 variables using external simulation program. Caldas et al. (2002) used Genetic Algorithm coupled with DOE as response generator in optimal sizing of windows in a building for optimal heating, lighting and cooling performance. Nielsen (2002) prototyped an optimisation system in Matlab using direct search simulated annealing algorithm to find the geometry and mix of building components that gives optimal performance. Other examples of optimisation of building envelope can be found at Marks (Marks 1997) and Bouchlaghem (Bouchlaghem 2000).

Applications in system optimisation can be found at Wright (Wright et al. 2002), in which multi-criterion genetic algorithm has been used to investigate the pay-off between the HVAC system energy cost and occupant thermal discomfort; and at Gustafsson (Gustafsson 2000), in which Mixed Integer Linear Programming (MILP) is used to retrofit building by optimising HVAC system and control strategies.

Apart from differences in objectives and algorithms used, these optimisation efforts can be categorized into two:

- Using hard-coded analytical equations of the underlying principles of building thermal design (Marks 1997, Bouchlaghem 2000),
- Using black-box approach, in which external simulation programs are coupled with optimisation algorithms to achieve a more realistic solution to the problem (Caldas 2002, Nielsen 2002).

The latter offers more flexibility in the formulation of the problem and hence the solution which can also be used to solve problems of varying resolution. The objectives are like "black-box" functions, which supply output for a given input through simulation runs without the user needing to know the details of underlying technology. This approach also allows the use of matured and well-behaved building simulation models and lets user focus more on the optimisation then validating responses.

## CONSIDERATIONS

For an optimisation tool to be incorporated in the design process, sharing and exchange of building information among various processes and software need to be seamless. Increasing dependency on computer-based tools during all life-cycle stages from conception to recycling and reuse makes it more vital. Moreover, the proposed tool needs to have flexibility in the formulation of optimisation problem and the use of algorithm to fit in varied design scenario. This section describes two of the most important concepts behind the development of ArDOT.

### Information modelling: Description of the building

The role of optimisation in environmental design of buildings is to help professionals take decisions to bridge the gap between design ideas and reality. It is thus necessary to extract and archive design information in a format that is understood by other stakeholders in the process. Deployment of building product models, theoretically addressing the semantic relationship among all elements, and containing data describing building is the only realistic way. IFC (Industrial Foundation Classes), a neutral AEC (Architecture, Engineering, and Construction) project model representing the AEC building lifecycle information, published by IAI (International Alliance for Interoperability) (Eastman 1999) has been chosen for implementation in this research. Figure 2 shows the three possible ways to share data using IFCs:

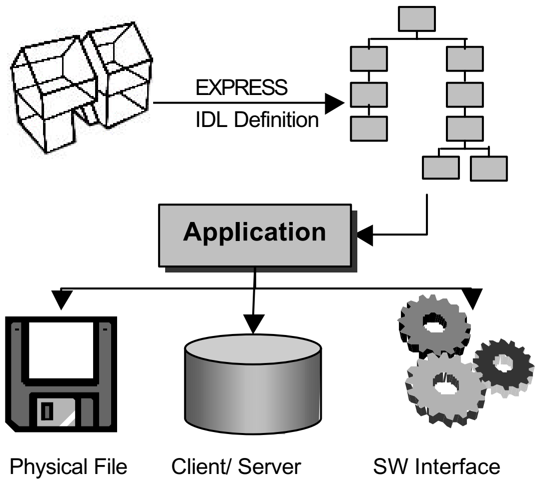


*Figure 2: Ways of IFC implementation (after IAI 1999)*

For (a) ease of design management, (b) elimination of data duplication, and (c) access to updated building information at any design stage, the client/ server method was implemented. Further IFC integration into design software may allow direct SW (software) interface to be integrated in ArDOT.

## Optimisation Algorithm

Efficiency of any optimisation algorithm to converge to optimum depends on:

- the number and type of design variables,
- the nature of the design space (linear, non-linear, continuous, etc.).

The optimisation problems in environmental design of buildings encountered by architects and building services engineer are usually multi-faceted. The number of design variables is usually large and the true nature of solution space can not be known because of the blackbox approach in coupling simulation software. The objective function may be linear or non-linear. Getting analytic derivatives from every simulation run to direct search process is not possible, rather they are obtained by finite difference methods. Therefore, it is necessary for a design optimisation tool to provide access to different types of algorithm to suit user needs. ArDOT facilitates the use of both gradient and non-gradient based algorithms through C API (Application Programming Interface) available in VisualDOC; a generic optimization software developed by VR&D (Vrand 2002). Using commercial optimisation libraries reduces the tedious task of testing and benchmarking of algorithms needed for hard-coded implementation. Detailed description of all the algorithms used in ArDOT can be found in Vanderplaats (Vanderplaats 2001).

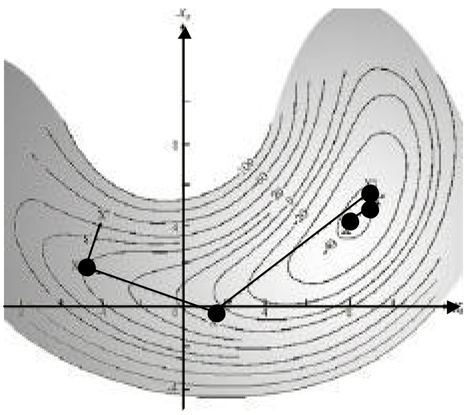

*Figure 3: BFGS and Fletcher-Reeves steps (after VR&D 2002)*

Gradient based optimisation

Both unconstrained and constrained minimization problems can be solved using gradient based optimisation algorithm. Figure 3 shows a gradient based minimization problem of design problem. Following gradient based methods are implemented in ArDOT:

- Unconstrained:
  - Broydon-Fletcher-Goldfarb-Shanno,
  - Fletcher-Reeves,
  - Sequential Unconstrained Optimisation.
- Constrained:
  - Sequential Quadratic Programming,
  - Sequential Linear Programming,
  - Modified Method of Feasible Directions,
  - Sequential Unconstrained Optimisation.

Design of Experiments

A common situation while using external simulation tools where designer does not know the exact underlying relationship between responses and design variables but wants to know how the responses are influenced by the design variables. In design of experiments, the relationship is explored through an empirical model or response surface: $y_i = f(x_1, x_2,..., x_n)$, where $y_1, y_2,..., y_m$ are response variables of interest and $x_1, x_2,..., x_n$ are design variables or factors. Figure 4 shows design space of an optimisation problem where Design of Experiments can be applied. A 5 zone building with reactive HVAC system installed were simulated using EnergyPlus changing area of glazing (% of wall) and azimuth (angle of the building with true north). Resultant cost of energy for two design days (summer and winter) is also shown in EURO.

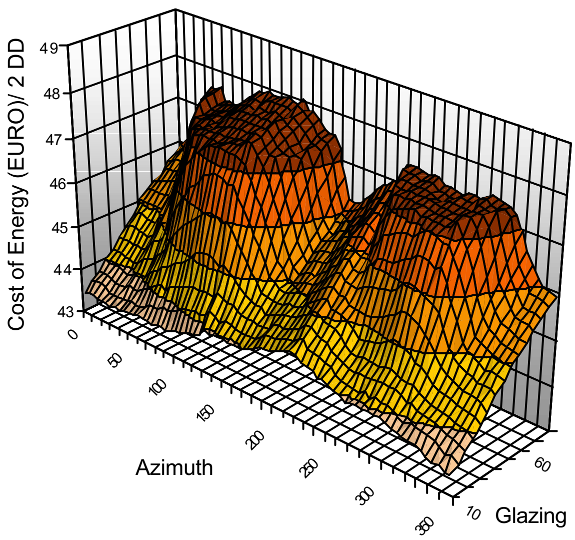


*Figure 4: Design space suitable for Design of Experiments*

Response Surface Approximate Optimisation

The basic idea is to create explicit approximation functions to the objective and constraints, and then use these when performing the optimization. The approximation functions are typically in the form of low-order polynomials (linear or quadratic) fit by least squares regression analysis.

Non-Gradient based optimisation

Genetic Algorithm and Particle Swarm Algorithm are the two Non-Gradient Based Algorithms used in ArDOT. Genetic algorithm method is suitable for solving problems where all the design variables are either integer or discrete, and the particle swarm method is suitable to deal with any mix of continuous, discrete and integer design variables.

## SYSTEM DEVELOPMENT

For flexibility and development, ArDOT has been designed in a modular fashion containing 3 main parts:

a. ArDOT Engine
b. Response Generator
c. IFC Repository

### ArDOT Engine

Optimisation activity starts with the Building information obtained through querying the IFC Model Server and presented to the user in graphical format. The user then formulates optimisation problem by choosing design variables, bounds associated with them, constraints, and type of optimisation algorithm. I/O Processor inside ArDOT transforms IFC data into inputs, handles calls to the optimisation engine, makes necessary changes in the input, and calls appropriate response generator(s). Responses back from the response generator (simulation software) are processed and sent back to optimisation algorithm to compute finite differences

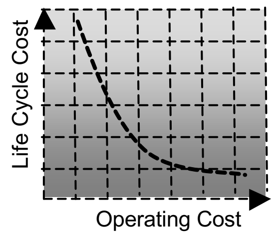


*Figure 5: Example pareto curve for pay-off study*

and direct search process. Results from optimisation activity are refreshed and sent back to the IFC database for archiving and design documentation. As most of the environmental design problems are multi-disciplinary and multi-objective, generating one single optimum may not be suitable to study pay-off characteristics. To facilitate pay-off study, a set of pareto optimal solutions can be produced as in figure 5, which shows possible pay-off curve between operating cost and life-cycle cost, where every point in the curve is a design solution. These sorts of curves assists designer in situation where a trade-off need to be made. For example, installing double-

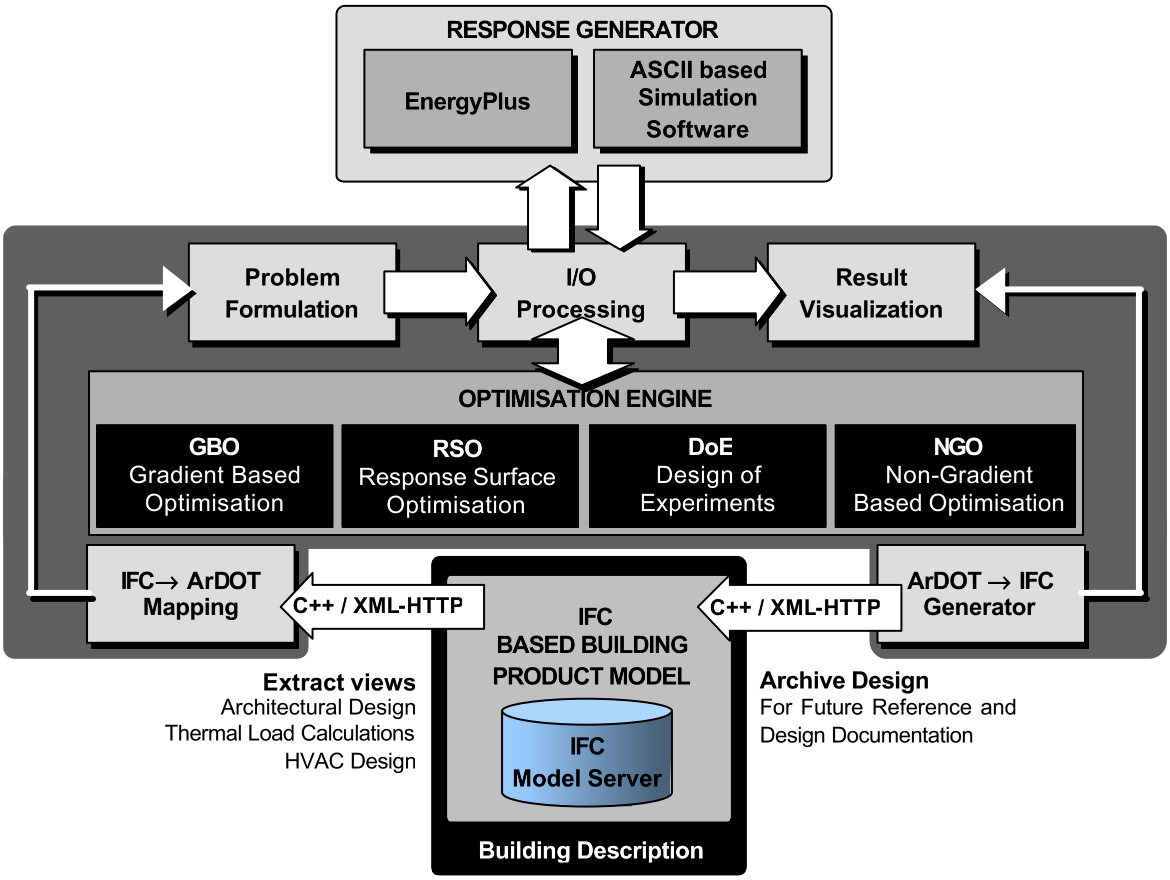


*Figure 6: Components of ArDOT*

glazing in windows may reduce utility bill, but has a high associated capital/ life cycle cost. The curve shows that an increase in life-cycle cost reduces the operating cost, but up to a certain extent.

## Response Generator

Any simulation software handling ASCII based input and output files can be coupled with ArDOT. For test case implementation, the authors have coupled EngeryPlus, an integrated and whole-building simulation software that builds on the strengths of previous initiatives BLAST and DOE-2 for accurate temperature and comfort prediction. Simulation capabilities of EnergyPlus include integrated simulation, combined heat and mass transfer balance, multi-zone airflow, HVAC loops (flexible system and plant simulation), links to SPARK and TRNSYS system/plant simulation and algorithms from the new ASHRAE loads toolkit (Crawley et al. 2001). The underlying building thermal zone calculation method in EnergyPlus is a heat balance model that gives a good understanding of interactions among different variables. The fundamental assumption of which is that air in each thermal zone can be modelled with uniform temperature throughout. The other major assumption in heat balance models is that room surfaces (walls, windows, ceilings, and floors) have uniform surface temperatures, uniform long- and short-wave irradiation, diffuse radiating surfaces, and one-dimensional heat conduction. However, for accurate analysis, computational fluid dynamics (CFD) - a complex and computationally intensive simulation of fluid (in this case, air) movement can be incorporated into ArDOT provided that the computing power needed for lengthy simulations becomes available and CFD tools become more simple to use in the design development stages.

## IFC Repository

Researchers and professionals in the AEC industry have begun to realize the potentials Building Product Models offer. International initiatives geared towards setting up standards for data model in the industry has gained momentum. Major vendors have released versions of their software adhering to these standards (e.g. IFC). Among the three ways IFC can be implemented "Client/ Server" method has been chosen to facilitate (a) the use of updated design information at any particular time without the need to redefine data and (b) archival of the designs produced during optimisation.

EDM (Express Data Manager), developed by EPM Technology has been chosen as IFC model server for implementation. EDM provides a framework for implementing and connecting software applications for sharing of industrial data in product's design and operational life. It provides the necessary middleware to establish a shared database environment and interfaces to Java and C/C++ without the need to install 3rd party DBMS (DataBase Management Systems) (EDM 2002). EDM complies with the international standards for "Industrial Automation systems and Integration - Product Data Representation and Exchange"; better known as ISO 10303 and STEP (STandard for Exchange of Product model data) (ISO 1994). IFC, based on the structure and framework of STEP and specified using EXPRESS (ISO 1991); is also supported by EDM. IFC Entities and attributes are accessed through C++ API and processed in ArDOT for input preparation. After optimisation runs, resultant design iterations processed again and mapped to IFC for archival in the IFC model server.

## CONCLUSIONS

This paper describes ongoing efforts to integrate simulation tools in design and argues that simply focusing on the process, interoperability, or decision-making is not enough to solve the problems. Also discusses the limitations of graph based visualization and decision-making for n-dimensional design problem. This establishes the need for formal optimisation methods to search the design space effectively. A brief discussion on previous attempts at optimisation activity in environmental reveals that too much emphasis has been put on the AI based techniques, which are not necessarily the most effective. Examples of which merely show that optimisation can be applied, but a coherent software environment is missing altogether that can be used in real life scenario.

This paper also presents ArDOT and its components and attempts to show the improvement that can be achieved by incorporating 'process-centric' 'task-based' 'decision-making' approach with interoperability in mind. The unique feature is that ArDOT is flexible in problem definition, visualization, decision-making, and search of n-dimensional design spaces, which offers significant improvement over existing simulation engines or other interface-development initiatives. ArDOT not only facilitates optimisation by running analysis in a number of simulation engines but also allows designers to analyze problems of varying domain resolution (e.g., from choosing the shape at the beginning to selecting system properties at detailed stage). IFC is implemented on a 'shared repository' basis with added classes to facilitate design archival and reuse throughout all life-cycle stages, which is different from other file-based prototypes to transfer geometry.

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