AN INTEGRATED MODEL FOR ENERGY-EFFICIENT BUILDING OPENING DESIGN

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The study uses system dynamics to develop a model that pinpoints the integration of a number of energy-efficient building practices that should be considered for building opening design. Examples are building commissioning, energy simulation, measurement and verification, carbon dioxide monitoring as well as automatic controllability. This may involve a compromise between aspects related to energy consumption, natural ventilation and lighting as well as noise control. In this regard, a stock and flow diagram are used to represent the integration of building opening design parameters, such as; orientation, window to wall ratio (WWR), glazing type and properties, cross-ventilation as well as applying daylighting controls using shading techniques. Hence, integration of design optimization techniques is performed for opening design of a residential building prototype in three different climate zones in Egypt; hot humid, moderate humid and hot arid-with 32 simulations for each location. The results indicate that the WWR provides an optimum solution while reducing energy consumption and emissions in all three climate zones. The results will assist practitioners in the proper selection of passive green building elements and techniques and the proper integration of energy-efficient practices.

Keywords: commissioning, simulation, verification, design, monitoring, control

INTRODUCTION

Any sustainable building process should aim at achieving 1) design optimization, 2) define measurement methods and benchmarks to compare performance against intended targets, 3) determine robust criteria for quality-verification as well as monitoring and feedback mechanisms to identify corrective actions (Muldavin, 2010). Hence, this study develops an integrated feedback stock and flow model to represent building-opening design parameters and their interrelations that reflect the complexity of the design problem; this includes building-opening design, orientation, material and any used shading device. This calls for an integrated view to the major role played by building-opening design in controlling indoor visual, thermal and acoustic comfort along with achieving energy efficiency and how it is practically impossible to act on one parameter without affecting others. (primary research objectives). Nevertheless, it is a challenging task for designers that necessitate viewing them as subcomponents of a larger system integration model to reach higher building performance targets as shown in Figure 1. Hence, this study uses system dynamic modelling tools to optimize building opening design using the interrelations of energy-efficient building practices (secondary research objectives). Examples are energy simulation, building

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commissioning (Cx), measurement and verification plan (M&V), carbon dioxide (CO_2) monitoring as well as automatic controllability.

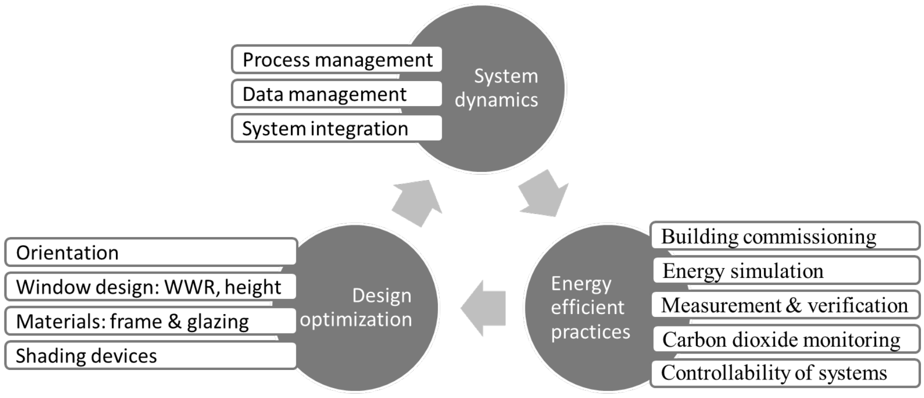

Figure 1: The conceptual approach of the research

LITERATURE REVIEW

This section presents the dual-tier objectives of the research. This includes discussing building-opening design optimization parameters on one hand and the interoperability of energy-efficient building practices for sustainable performance and data management on the other hand. Hence, an updated literature search was carried out using Science Direct database from 2010-2020. This included electronic books as well as peer-reviewed journal and conference publications. The search used the following keywords; building commissioning, energy simulation, measurement and verification process, opening design, monitoring and control systems. This outlined the different perspectives undertaken and identified relevant research gaps and limitations. It was noted that the number of relevant papers showed increased worldwide attention to the subject. It also indicated common areas with intelligent building application, daylighting and glare simulation and control as well as optimisation design for building-opening and façade designs to achieve energy efficiency.

Design Optimisation for Building-Opening Design

Previous studies pointed out the need for optimizing building-opening design to achieve a balance of multiple objectives; daylighting and visual comfort, thermal performance as well as energy savings. This included aspects associated with building-opening design as well as the ratio of window area to floor area, building location, orientation and surrounding obstructions as well as characteristics of the building envelope and glazing areas. Examples are the Solar Heat Gain Coefficient (SHGC), thermal resistance (u-value) and Visible Light Transmission (VLT); noting that high VLT and low SHGC should be achieved (Kirimtat *et al.,* 2016). Further considerations included the use of light shelves and shading devices (manual and automatic) for enhancing the efficiency of indoor light distribution and visual comfort. For measuring daylight, previous studies used Spatial Daylight Autonomy (SDA) and the Annual Sunlight Exposure (ASE) to assess visual comfort (Galatioto and Beccali, 2016).

A previous study investigated the ideal WWR for a southern facade window in an office building in Tehran through computational simulations. Then, the effect of horizontal solar shading was tested using the Ecotect and Radiance software programs. The results showed that a 5% increment in WWR of 15%, 20% and 25%

achieved a 10% incremental improvement in daylight efficient ratio and for a WWR of 30% and 60% only a 2% increase was achieved (Mahdavinejad *et al.,* 2011). Another experimental study by Choi, Lee, and Jo (2017) showed that buildings with movable shading devices stored up to 48% of the whole energy consumption.

System Thinking for Sustainable Project Management

The science of system thinking is emerging as a new approach for decision-making of issues related to sustainable buildings along their life cycle (Thompson and Bank, 2010). It allows the integration with BIM technologies and other advanced modelling software programs (Bank *et al.,* 2010). It has been used to discuss aspects related to energy efficiency. Nevertheless, the use of system thinking modelling approaches and calculation methods for building-opening design is considered a new field and the search for optimization techniques is still a work in progress.

The Interoperability of Energy-Efficient Building Practices

The use of advanced energy-efficient building practices is widely increasing in the international marketplace. These processes should not be looked upon in isolation because after all, they aim at achieving almost the same green goals but acting on different sustainable criteria or life stages. They can be applied for the whole building level or individual building elements (Ismaeel, 2020). For this research, they can be used for the process of building-opening design optimization.

Energy simulation is performed to support decisions taking place during the design stage to be able to manage the complexity of calculations and compare design alternatives. Performing the Cx process is also vital to support life cycle costs and long-term performance during building operation and management. The M&V plan provides performance feedback and adjustments. Moreover, the Post Occupancy Evaluation (POE) may also be used to consider the qualitative aspects that evaluate a buildings performance in defined time limits. CO2 monitoring and automatic controllability are carried out during the operation stage. They may be associated with a centralized automatic control network to achieve energy efficiency while achieving indoor occupants' comfort by using real-time occupancy and activity (Muldavin, 2010).

The integration of energy-efficient building practices has been proposed by Ismaeel (2020) based on a set of criteria that have been defined by literature review and validated through an online questionnaire among local practitioners as shown in Table 1. The result showed that all energy-efficient practices are strongly related to the green building process, they are relatively easy to apply-provide the existence of proper guidelines. The study also showed that they may vary for capital cost and long-term savings; highest for energy simulation and least for M&V plans, and extra time is seen for the M&V plans. Furthermore, it showed that additional expertise is needed to carry energy simulations to develop the model and provide all necessary detailed input data, nevertheless, this process is associated with the greatest percentage error and this explains why it should be integrated with other energy-efficient practices for verification, control and feedback.

METHOD

This study aims at presenting a systemic approach for optimizing the building-opening design in terms of providing indoor visual, thermal and acoustic comfort as well as building energy efficiency as shown in Figure 2. This investigates different parametric design variables based on previous literature; orientation, Window to Wall Ratio (WWR), glazing type and properties (light transmittance, G-value and U-value), cross-ventilation as well as applying daylighting controls using shading techniques.

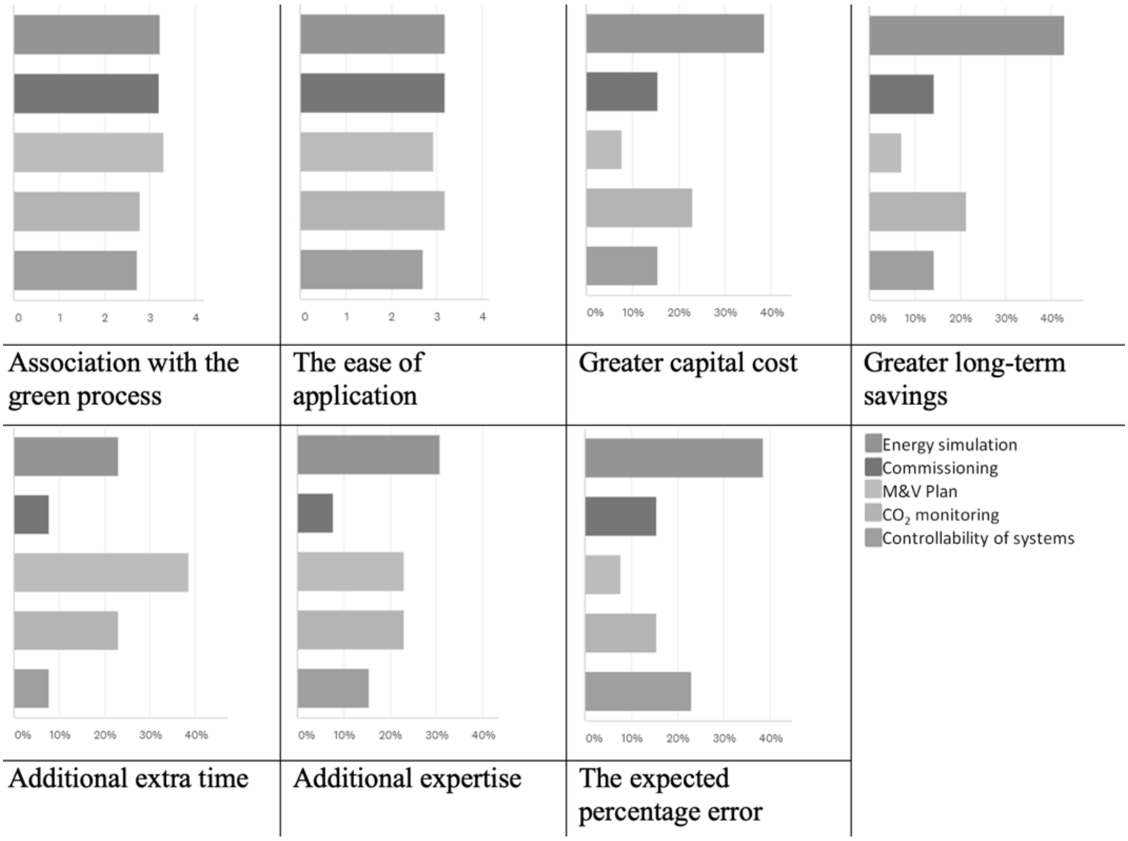

Table 1: Investigating the integration of energy-efficient practices (Ismaeel, 2020)

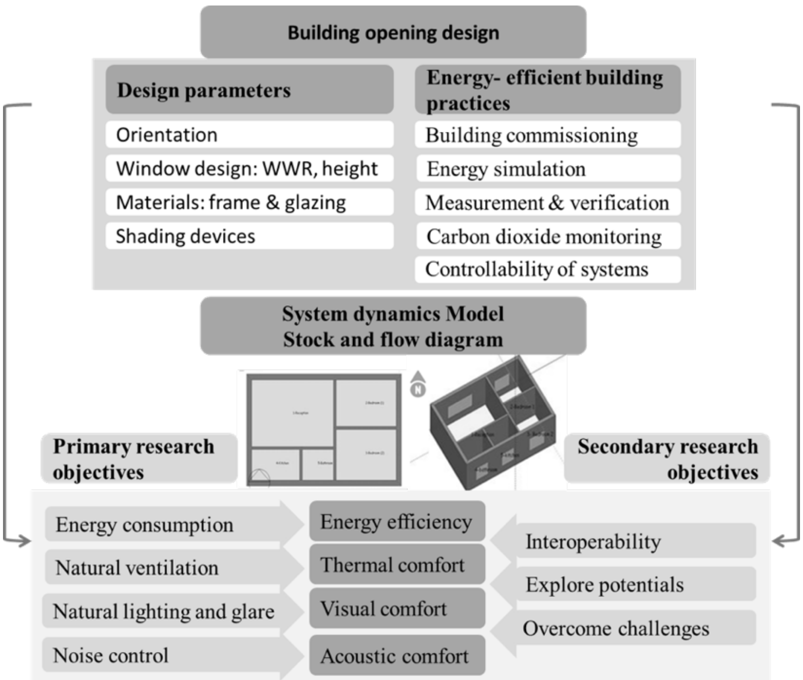

Figure 2: The research methodology

To calculate the total energy consumption (kWh) and indoor temperature (^oC), the building simulation tool (Design Builder) is used which operates based on the Energy

Plus-version 7.2; noting that the latter is a validated simulation tool that performs heat-balance models to calculate buildings thermal performance.

It allows for an hourly-calculation of operative temperatures and space-heating demands based on accurate solar radiation analysis (DesignBuilder, 2020). Moreover, the DIVAs scripting interface was used for radiance analysis to be able to calculate the daylight factor, and annual SDA and ASE (Kröner *et al.,* 1990). Radiance software was developed in the Lawrence Berkeley national laboratories and validated against real measurement (Radiance, 2020). It is also noted that the rates of natural ventilation in non-air-conditioned residential buildings were calculated according to the Egyptian national code for improving energy efficiency in residential buildings. The simulation was repeated for three different climate zones (with 32 simulations in each location); hot humid (C1), moderate humid (C2) and hot arid (C3) to test the combination of different design parameter and indicate the optimised case scenario.

The building model is a typical example of a modern single-story family residential unit (according to national building codes and local building regulations). It is 3 m height (floor to floor) which includes one reception, two-bedroom, kitchen and bathroom with a total area of 50 m^2; reception area 3.6x4.2 m, bedroom (1) 3.1x3.2m, bedroom (2) 3.2x3.6m, bathroom 1.8x1.5 m and kitchen 1.5x2.6m. It represents local materials and best practices. The 25 cm brick external wall is externally finished with 2 cm lightweight plaster and 2 cm cement mortar. It is internally finished with 2 cm cement mortar and 20 cm sandstone. A single glazing of 6 mm clear glass is used. Furthermore, the roof is composed of 12 cm reinforced concrete layer, 7 cm cement paste, insulated by 5 cm cork layer and 2 cm damp proof course (D.P.C.), covered by 10 cm sand, 2 cm mortar and 2 cm cement tiles. Also, the infiltration rate is set at 1.25 air changes per hour and the light power density is 21 W/m^2. Table 2 describes the model design parameters.

The results of the energy simulations require further checking using the Cx process to avoid common design errors, construction mistakes and defective equipment, as well as monitor its basic operation, and maintenance process. This raises the quality assurance process and provides better documentation for the performance of the building opening design and its contribution to the overall building performance. Then a more comprehensive check is provided as part of the M&V process to take any required amendment actions and provide continuous monitoring and feedback mechanisms.

The next step applies the science of system thinking to represent the complexity of optimising the building opening design process and the effect of interacting parameters. Hence, a stock and flow data-processing diagram is developed using Vensim PLE 7.1 software to act as an efficient method of defining the interrelations and problematic areas for the building model with the following deducted integrative index as shown in Table 3 referring to Ismaeel (2020).

This shows the limits of the study boundary, subsystems and causal effect interrelationships for an improved understanding of all associated design parameters. Putting them in a larger system model shows design complexities and their effect on the state of building opening design efficiency through feedback loops which rises as a result of their internal structures and governing decision rules.

This conveys information on the limits of the study and level of aggregation by showing the number and type of different sustainable parameters and provide a useful exploratory for viewing buildings as systems.

Table 2: Building model parameter variations

Parameter	Variations
WWR	20% and 40%
Glazing type	Single (u-value)
	Double (u-value)
Cross-ventilation	Single opening
	Double opening with the same heights
	Double opening with different heights
Shading type	Applying shading device
	No shading device applied
Orientation	North, South, East and West

Table 3: The deducted integrative index of each discussed green building practice, (Ismaeel, 2020)

Variables	Energy simulation	Cx	M&V	CO_2 monitoring	Systems' control
Association with the green process	3.23	3.20	3.31	2.79	2.71
Ease of application	3.17	3.17	2.92	3.17	2.69
Long term savings	4.20	1.40	0.70	2.10	1.40
Capital cost	3.80	1.50	0.77	2.30	1.50
Extra time	2.30	0.77	3.80	2.30	0.77
Additional expertise	3.00	0.77	2.30	2.30	1.50
Expected error	3.80	1.50	0.77	1.50	2.30
Total integrative index*	0.31	1.46	0.40	0.60	0.74

*Total integrative index $f(x) = \frac{\sum_{L3_{i=1}}^{n} x_{L3_i}}{n} - \frac{\sum_{L4_{i=1}}^{k} x_{L4_i}}{k}$

RESULT

The study discussed the use of system dynamics to develop an optimization model for building opening design. This included energy-efficient processes and practices such as energy simulation, Cx, M&V plan, CO_2 monitoring and automatic controllability. The results showed a proposed optimization model exploring their interrelations through a stock and flow data-processing diagram to optimize building opening design as shown in Figure 3. The results showed duel-tier benefits for building-opening design parameters on one hand and the interoperability of energy-efficient practices on the other hand. The influence of modifying design parameters was discussed as follows;

The effect of changing the WWR

For visual environment and natural ventilation rates, daylight was directly proportional with the opening size in simple relation, hence, the duplication of the size leads to duplication in average daylight factor. For thermal performance, the average temperature increased by 1^{o}C when duplicating the opening size. For energy consumption, it is found that duplicating the WWR from 20% to 40% lead to an increase in energy consumption. The east and west-oriented spaces were the greatest in energy consumption, followed by the south and north ones. Hence, the results showed that changing the WWR from 50-20% did not significantly reduce the cooling loads but daylighting levels were significantly reduced.

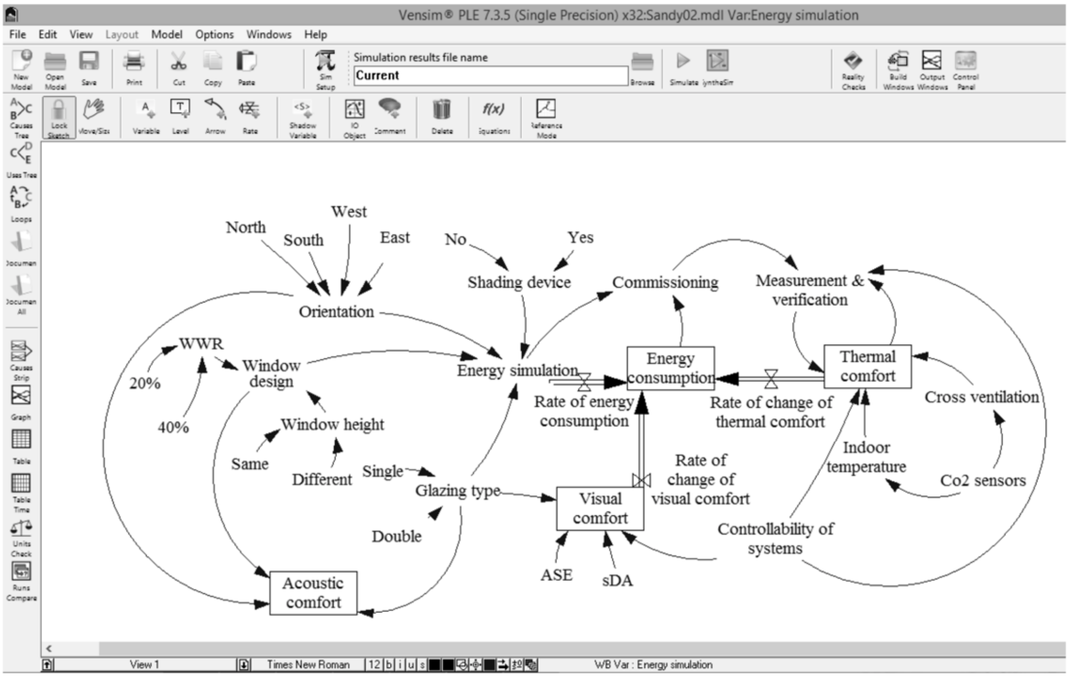

Figure 3: The Vensim model showing a stock and flow data-processing diagram to optimize building-opening design

Shading devices (overhangs, side fins and louvres)
the total cooling loads showed that side fins did not reduce cooling loads significantly but overhangs had a substantial impact of (18-20%) reduction for C2 and C3; and louvres had their greatest impact in C3 (14%) which was west-oriented, then C2 (11%) which was south-oriented and the case of using louvres recorded the largest impact reduction in daylight levels.

The glazing properties
The total cooling loads showed that double-glazing did not have an evident impact on load reduction. Using double low-E glazing had a greater impact on loads, especially in C2 and C3 (6-8%). Finally, using single glazing with low solar transmittance factor had the greatest impact on reducing loads, especially in C2 and C3 (14-15%).

Then, computer modelling, and simulation techniques were integrated with optimization methodologies to offer opportunities to evaluate multiple criteria design decisions. Nevertheless, the accuracy of energy simulation models was bound to the range of data input which may not be accurate at early design stages. This gives inaccurate indications concerning building performance. Thus, the Cx process is important to carry validation and verification checks and performance tests. This is in addition to creating archived O&M manuals and schedules as well as warranties and datasheets. Nevertheless, the expected risk arises from the lack of generally accepted industry guidelines and standards (Harmer and Henze, 2015).

The M&V process provides regular and long-term savings to the building; nevertheless, this may require installing building automation systems. Some of the problems with applying the M&V plan include lack of past utility data, building-level utility meters or other means of following-up after project completion, this is in addition to the lack of energy management control systems (Harmer and Henze, 2015; Granderson *et al.,* 2016). The result indicates great commonalities between the aforementioned practices; in sharing system-energy data and engineering-saving assessments; noting that the data collected for the Cx process may act as input data for the M&V plan and provide a reference to check the operational verification and energy saving calculations of the energy model.

The M&V should optimally begin during the Cx process to validate its procedure. The Cx process requires performing trend-analysis to test equipment functional operation after they are installed and including CO_2 sensors calibration in both the Cx and M&V plans. This is associated with the M&V operational verification requirements and indicates that applying system integration is the key to attain better performance targets (Komínek, Weyr and Hirš, 2017).

DISCUSSION

The role played by building opening design is significant to achieve energy efficiency as well as occupants' comfort and productivity. The study discussed its complexity for a residential building- which accounts for 60% of building stock in Egypt (ElGohary and Khashaba, 2018). The result provides dual-tier benefit; it can be incorporated in local building laws and codes, furthermore, it may assist practitioners for the proper selection of passive green building elements and techniques. This stresses the need to develop practitioner's knowledge concerning system thinking and application.

CONCLUSION

The study applies system thinking and modelling approach as a basis for providing an integrated approach. It develops a stock and flow data-processing diagram to optimize building opening design. Design parameters included WWR, orientation, glazing type and properties, cross-ventilation as well as applying daylighting controls using shading techniques. The model was applied on a case study-residential building-in three climate zones in Egypt- showing that changing the WWR provided an optimum solution while reducing energy consumption and carbon emissions in all three climatic zones.

This put forward a systemic approach to achieve energy efficiency as well as thermal, visual and acoustic comfort. Nevertheless, it is a challenging process particularly with the several variables in hand and their dynamic and implicit interactions. Hence, the author presented fresh perspectives and insights of using system integration of several green building processes and practices that shared a common aim of maximizing energy savings and showed the interoperability of these practices in wider building management plans and applications, these include building commissioning, energy simulation, measurement and verification, carbon dioxide monitoring as well as automatic controllability. This should be considered during early project stages to create an iterative process of joint-inquiry and develop novel comprehension of the dynamic complexity of its interrelations.

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