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Mapping failures in energy and environmental performance of buildings

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Abstract

Buildings regularly fail to perform at optimum levels and often do not meet design predictions. These failures impact energy efficiency, provision of adequate indoor environmental quality (IEQ) and occupant satisfaction. Detailed energy audits of 33 office buildings in Brazil are used to map and categorise the performance issues which lead to energy inefficiency and inadequate IEQ. Four buildings use occupant satisfaction questionnaires to complement the audit and evaluate the impact of failures on users. A total of 333 failures are identified and categorised in 51 separate modes. The causes of failures are identified as errors in building design and construction (D&C) or operations and maintenance (O&M). Some issues require retrofit procedures, but most can be corrected by adapting O&M procedures. Small- and medium-sized offices generally repeat the same failure modes; automated procedures or checklists and training could optimise performance in these buildings. Large offices are likely to require commissioning expertise in newer buildings, while older buildings require automation systems or full retrofits. The effects of O&M and building management are seen to have greater impacts on performance and occupant satisfaction than factors such as design, year of construction or building HVAC system.

Keywords

Commissioning; Energy Efficiency; Indoor environmental quality (IEQ); Occupant satisfaction; Performance gap; Performance optimisation.

Highlights

- Buildings often fail to meet standards of energy efficiency, IEQ and occupant satisfaction.
- The failure modes are categorised and evaluated by impact and correction procedures.
- O&M procedures have the greatest impact on performance and occupant satisfaction.
- Significant energy savings and comfort improvements can be achieved by correcting failures.

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- In small- and medium-sized buildings, procedures can be automated.

Introduction

Energy is used in buildings to provide a series of services to the users, including environmental control for occupancy conditions. Research on energy efficiency in the built environment has focused on ways to provide these services with lower levels of energy consumption [1], and a wide range of methods for evaluating performance have been developed in recent years [2]. The services provided in the buildings will vary according to the building type and its main uses. In office buildings, they will generally include thermal comfort, air quality, lighting and people transport. Equipment in the building will also use energy to provide data processing services, through central servers and individual computers.

Thus, any of the three following cases could be considered a performance failure in a building:

1) Indoor environmental quality (IEQ) parameters are not met;
2) Excessive energy is used and high operational costs are incurred unnecessarily; or
3) Users report low satisfaction or productivity.

In some cases, a building will have failures in several of these areas simultaneously and could be considered an “unhealthy” building – corrections will need to address the areas together. In other cases, there may be conflicts between the areas, such as when a building has an inadequate external air supply – correcting this will improve indoor environmental quality but increase energy consumption.

Failures may be caused by the design, construction, maintenance or operation of a building and may have a wide range of different impacts, from health to productivity to excessive operating costs. Mapping the failure modes prevalent in a specific building typology can create an evidence base for improving performance, and for providing feedback and information to building users and operators.

Leaman et. al. [3] describe the practice and performance of building performance evaluation, identifying the techniques as “real-world research”: field-based, problem-oriented, time-constrained, multidisciplinary and focused on providing actionable results to a client. There is an inherent challenge in adapting the results from individualised building surveys to draw broad scientific conclusions, but this bottom-up analysis provides the most effective way to understand and correct the real operational issues faced by buildings.

Literature review and existing studies

The energy performance of buildings is a subject which has received a rapid increase in interest and research over the past years, as the importance of buildings in meeting global carbon emissions reductions targets has become apparent. A wide array of literature focuses on improved energy performance for new buildings, through energy modelling, integrated design and bioclimatic architecture [4]. As energy efficiency in new buildings has been increasingly measured and evaluated, the existence of a "performance gap" between expected and measured energy consumption of buildings has become clear [5]. This performance gap has a range of causes, of which the most significant are identified as uncertainty in modelling, occupant behaviour and poor operational practices [6].

Work on improving the performance of buildings often focuses on the opportunities for retrofit, by the installation of new systems, often replacing existing systems on a like-for-like basis (for example, exchanging light bulbs). This has the advantage of being simple to model and provides important information to support the development of policy on energy efficiency in buildings, or to justify new investments through performance contracts. However, this type of analysis is often limited to simple technological upgrades and will generally assume that environmental conditions were identical before and after the retrofit. Measurements of the "rebound effect", particularly in retrofitted dwellings, have shown that this assumption may overestimate savings [7], [8].

Ruparathna [9] separates energy performance opportunities in existing buildings into:

- Technologies & assemblies;
- Energy management; and
- Occupancy & operational requirements.

The potential energy savings from efficient technologies & assemblies are well-documented and include HVAC upgrades, heat recovery, lighting upgrades, increased lighting automation, building envelope upgrades and local micro-generation. However, other potential energy saving benefits are broadly grouped together under headings such as commissioning, monitoring and "energy efficiency culture". While many studies have shown the benefits of both commissioning [10] and simple energy management [11], there are few bottom-up studies on the mechanisms by which these measures save energy in different building types, or the operational failures which are corrected by these measures. Table 1 provides an alternative division of the type of improvement actions for building energy and environmental performance, separated by the type of action required rather than the technology.

Table 1 – Actions for improving energy and environmental performance of buildings

Type of action	**Description**
User behaviour modification	Increasing awareness of energy consumption among users so that they take more responsibility for reducing their own consumption, without the need for any technical interventions.
Correction of performance failures	Modification of building systems or operational parameters to optimise performance by correcting problems which may have been introduced in building design, construction, refurbishment, maintenance or operation. This includes most existing building commissioning procedures.

Substitution of major systems	Direct exchange of lighting, air conditioning or other systems in a like-for-like retrofit scenario, as systems become inefficient or reach the end of their useful lives.
Full building renovation	A whole-building refurbishment or major systems renovation, which requires substantial redesign and can incorporate most of the efficiency techniques which would be employed in new building design.

A major review on building controls failures identified 384 control-related problems in more than 118 buildings [12]. Of the problems identified, 32% were due to hardware, 35% due to software and 21% caused by human factors (the remaining 12% had unspecified causes). Major recurring issues were identified with set points or schedules, improper logic and malfunctioning economizers.

The discipline of building energy commissioning has expanded rapidly in recent years, and now includes retro-commissioning, recommissioning and continuous commissioning, with a series of technical procedures and publications defining processes for identifying and correcting building performance issues [13]–[16]. Automated building commissioning tools are being developed [17], [18], and a range of analysis methods for automated fault detection focus principally on air-handling units (AHUs) and chillers [19]–[26]. A study on improving operational energy performance of buildings identified 21% energy savings through “realistic changes in current building operation patterns” [27], while a broader framework for building performance optimisation highlights the need for links between modelling approaches and implementing appropriate control and automation strategies [28].

However, a common factor in most existing studies is that they either focus on specific types of equipment, such as chillers, or try to draw broad conclusions regarding buildings in general. Proposals for corrections of performance failures in buildings almost exclusively assume that basic environmental and user satisfaction criteria are being met, while the solutions presented either require skilled and expensive building commissioning professionals, or interconnected building management systems providing large quantities of high-quality data which can be subjected to automated analysis techniques.

Office buildings in warm climates and emerging economies are likely to encounter a wide range of performance failures related to IEQ, efficiency and user satisfaction, but may not have access to full commissioning services, either due to the cost of the service or the lack of experienced personnel. Where building commissioning is carried out purely because it is mandated or required, it risks becoming an ineffectual bureaucratic exercise; regulation and consistency may be difficult to achieve [29]. An investigation of the failure modes in a specific building type can thus provide valuable insights in how to evaluate and improve performance across the building stock.

Indoor environmental quality has increasingly emerged as a key topic for research in recent years. The key factors for IEQ in office buildings are identified as: indoor air quality; thermal comfort; lighting & daylighting; noise & acoustics; office layout; biophilia & views, look & feel; and location & amenities [30]. Of these, the items related to air quality, thermal comfort, lighting and acoustics are those most likely to be affected by failures in building services, while the others are more likely to be related to building architecture and interior design or fit-out. Occupant satisfaction is clearly linked to productivity through these IEQ factors [31]–[34].

Finally, there is a range of literature on occupant satisfaction analysis in buildings. These studies are often questionnaire-based, using methods such as the CBE occupant satisfaction survey [35] or BOSSA [36], [37] to compare occupant satisfaction in LEED and non-LEED buildings [38], to relate satisfaction to indoor environmental quality [39] and to compare mixed-mode buildings with a generic dataset [40]. Large-scale surveys of building occupants suggest major failings in air quality levels and in thermal comfort, with most buildings not meeting design standards [41]. Green buildings in this dataset show slightly improved performance in thermal comfort and air quality, but worse results in acoustic and lighting performance [42]; studies in BREEAM buildings show a similar requirement to balance design considerations around privacy and perceived control with energy performance [43]. A review by Rupp et al of comfort in the built environment identifies dozens of field studies carried out in different typologies [44], but there is still a need to link poor occupant satisfaction to building system performance failures.

Methodology

Between 2015 and 2017, building performance analyses were carried out in 33 buildings in Brazil which function primarily or partially as offices. As shown in Figure 1, these buildings have a wide range of sizes, locations, usage types (public or private) and were built between 1929 and 2013. They cover several different climate zones, including five of Brazil's eight bioclimatic regions.

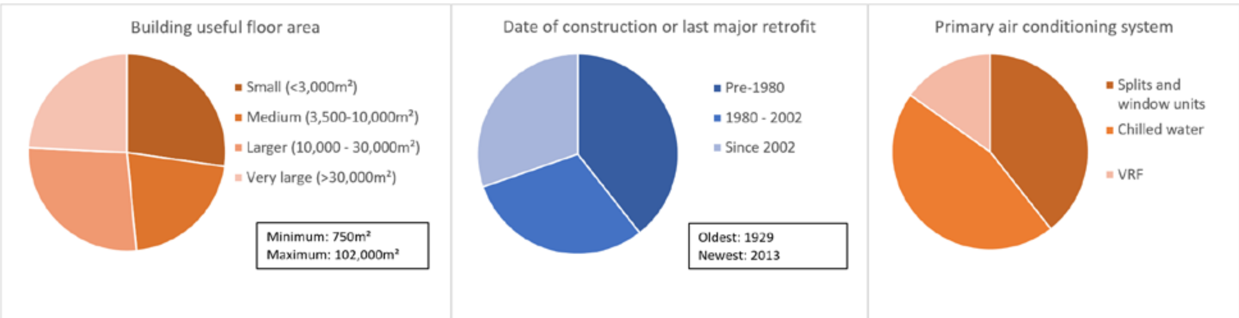

Figure 1 - Characteristics of buildings in the study (n=33)

The use of a single primary building type (office buildings in Brazil) removes some of the generalisations associated with broader studies and evaluations. All buildings in the study have air conditioning systems, artificial lighting, data processing, plug loads and elevators, although these vary significantly in size and importance. No buildings have significant water heating or space heating systems; energy consumption in all cases is dominated by electrical energy, and the onsite use of fossil fuels (for catering or emergency generators) is negligible.

16 of the buildings in the study are characterised as small or medium buildings; they have areas under 10,000m² and generally use simpler building systems. Nearly all have operable windows and can operate in mixed-mode when necessary; a majority have unitary direct expansion air conditioning systems (split or window air conditioners), the exceptions are two buildings with variable refrigerant flow (VRF) systems and another two with centralised chilled water systems.

The remaining 17 buildings in the dataset are characterised as large buildings; they all have areas over 10,000m², mean area is just under 32,000m² and they have more complex building systems, especially HVAC. With one exception (an old building with conservation status), all are fully conditioned with VRF or chilled water systems, usually using water-cooled chillers involving separate cooling towers. None of the buildings use economizers or variable air volume (VAV) distribution systems in the AHUs. This is important, as a significant proportion of the control errors found in the literature relate to problems with these systems [12], [45]. In other words, even large and relatively complex buildings in Brazil use simpler building services than their equivalents in developed economies, which may reduce the range of potential failures.

In each building, the following stages of work were carried out:

1) An energy audit was carried out following ASHRAE Procedures for Commercial Building Energy Audits [46], in accordance with Level 1 or Level 2, identifying a list of energy conservation measures, and estimating costs and annual savings.
2) A breakdown of energy consumption by end-use was estimated using CIBSE TM22 methodologies [47].
3) Interviews with key staff were used to identify performance issues and problems in the building.
4) Key data on the buildings' physical characteristics and occupational parameters were recorded.

In addition, four of these buildings received occupant satisfaction analyses, carried out using the Building Use Studies (BUS) methodology [48]. This methodology was developed in the 1990s as part of the PROBE studies, [49] and is now a commercially available questionnaire evaluation of user satisfaction in buildings. The analyses were carried out using web-based and paper surveys and a total of 884 individual responses were collected and evaluated. The analysis collects responses to a set of 48 questions, which are compared to international benchmarks developed from responses to the same questionnaire in other buildings. Qualitative data are collected via open comment sections. As this was the first time the BUS questionnaire had been applied in Brazil, some of the differences encountered were likely to have been intercultural, so evaluations were carried out comparing buildings in the study against one other. The questionnaire was administered either in the entire building, or else in a single floor, when it was impractical to evaluate the whole building. In each case, the responses received represented at least 50% of the occupants of the surveyed areas.

Each building received a report containing a list of recommendations for actions which should be taken to improve energy performance, environmental quality and occupant satisfaction. Several of these recommendations were related to like-for-like retrofit or exchange of components, as listed in Table 2. These measures represent significant energy and cost savings potential, but are not considered to be corrections of failures in building performance. The potential and importance of these types of measures are covered at length in literature related to retrofit programmes on energy in buildings [50]–[53], but are not considered further in this analysis.

It should be noted that the audits were carried out over a period of nearly three years by a small, multidisciplinary team. This may introduce small differences in results between some of the buildings, but great care was taken to train all the energy auditors in the appropriate techniques and to standardise the methodologies adopted across all the buildings.

Table 2 - Improvement measures related to substitution of systems in buildings

Substitution of major systems: retrofit measures for energy efficiency and comfort in buildings	
Envelope	Use of solar control glazing
	Increased surface reflectivity (light colours) on walls and roof
	Installation of external window shading or external vegetation
	Improved insulation levels of walls and roof
Lighting	Lighting upgrades – exchange of lamps for more efficient equivalents
	Lighting automation through presence or motion sensors in some areas
HVAC	Upgrades of chillers and split air conditioning units, or direct exchanges for more efficient alternatives
	Variable frequency drives for pumps
	Variable air volume distribution systems in air handling units
Other	Exchange of office equipment for more efficient alternatives
	Elevator upgrades (controls or full system replacement)
	Installation of building automation systems
Generation	Installation of embedded micro-generation, usually solar PV

Following the exclusion of the measures related to direct substitution of systems, the remaining measures related to performance improvement or corrections in the buildings studied were categorised as management, data processing, electrical, lighting or HVAC issues. A total of 51 separate failure modes were identified in the buildings, related to energy performance and indoor environmental quality. The levels of impact on building operation were categorised as low, medium or high and the action required for correction of the failure was identified. Some corrections merely require changes to user-defined processes or operational parameters, whilst others may be carried out by the maintenance team and some will require external commissioning professionals or even a full system retrofit procedure.

Most measures included estimates on costs of installation, annual savings and payback. As the energy audits were rapid (generally 1-2 days per building) and aimed principally at identifying and prioritising energy saving measures, the calculation methods used were generally simple engineering estimates or even rules of thumb. The levels of accuracy and consistency in the savings estimates are sufficient for a building owner or operator to decide whether to move ahead with further evaluation and full costing of measures. However, many measures related to environmental quality do not have paybacks or savings associated with them, and some may even increase energy consumption. Thus, the corrections to building performance having satisfied the criteria of being technically feasible, the cost and savings data are not considered further in this evaluation.

Results

The audit reports to the buildings identified a total of 333 separate failures (excluding retrofit measures), which were separated into 51 different failure modalities across the 33 buildings studied. These failures were divided into those relating primarily to environmental quality and those relating to energy performance, which are examined separately.

When the buildings are divided according to their age category (pre-1980, 1980-2002, post-2002), no significant differences are found in the frequency or type of failure. Of the three buildings with under five failures each, two are large (over 30,000m²) and one small (3,300m²), but the buildings were completed in 1974, 2001 and 2013. The feature all have in common is the high level of dedication of operations and maintenance teams.

Failures in provision of indoor environmental quality (IEQ)

Several of the buildings in the study failed on a basic level to provide basic conditions of indoor environmental quality, as demonstrated by the 13 different failure modes shown in Table 3. Only five of the 33 buildings studied did not report a single issue related to environmental quality. Most issues were related to the HVAC systems, which either do not provide thermal comfort or (in most cases) are not properly controlled. The most common problem, of unbalanced air distribution for cooling, was found almost exclusively in large buildings. The second most common problem, of inadequate lighting levels, was found only in small- and medium-sized buildings.

Table 3 - Failures in provision of indoor environmental quality in buildings

IEQ failure mode	Impact	Resolution	Frequency (sample=33)
Electrical supply or main incomer not properly dimensioned	High	Retrofit	3
Thermal comfort not met by undersized HVAC system	High	Retrofit	5
No external air supply (or insufficient external air)	High	Retrofit	3
Natural ventilation underused because of: lack of insect control mechanisms, excess noise, internal layouts	High	User	3
Sensors broken or not working properly	High	Maintenance	2
Chilled water flow valves are not working or have been removed or not installed	Medium	Retrofit	5
Inadequate lighting provision in some zones	Medium	Retrofit	8
Inadequate use of internal shading on windows	Medium	Operations	7
Excess noise requires provision of quiet rooms or areas	Medium	User	1
Unbalanced air distribution for cooling	Medium	Commissioning	10
External air flowrate unknown and uncontrolled	Low	Maintenance	7
Lack of control for air distribution within zones served by a single fancoil unit	Low	Retrofit	7

Thermostats incorrectly positioned and do not measure effective temperatures for occupants	Low	Maintenance	3

The complete failure of cooling control systems was frequent, with chilled water systems uncontrolled and sensors broken or missing. Issues linked to external air provision were also quite common, with 9% of buildings having no outside air supply at all, and a further 21% showing potential issues with uncontrolled external air, usually relating to very small or partially blocked outside air supply ducts. This issue should be further investigated, through measurement of air quality in offices which do not properly control or measure outside air, to identify the potential impacts on user health and productivity.

A significant proportion of the environmental quality issues raised here are linked to the system design. These are mostly found in older or smaller buildings and are all relatively simple issues which a simple design review or a commissioning process would have picked up rapidly. More common are the issues relating to ongoing maintenance in many of the buildings, which has caused performance to deteriorate even in correctly designed buildings. This includes a case where the chiller operates at only 40% of its design capacity and others where the two-way control valves on the chilled water circuit have been removed from the water pipes and not replaced; both issues are caused by poor maintenance.

It is important to note that meeting some of these environmental criteria may increase energy consumption slightly, while others (related to better control of cooling) are likely to reduce consumption.

Failures in energy performance

A total of 269 building performance issues were divided into 38 failure modes which relate to energy performance. These were encountered in the 33 buildings studied (energy impacts of the 13 failure modes related to environmental quality were excluded). Of these failure modes, 27 were found in small buildings and 36 were found in large buildings, while three of the failure modes occurred in just one building each.

The average number of failures in the large buildings was 11.5, while the average number in small buildings was 8.6. As can be seen in Figure 2, most performance failures encountered in small buildings were management failures; in fact, five types of management failure were responsible for 47% of the failures identified in this group. These failures related to: incorrectly negotiated energy contracts, procurement guidelines with no mention of energy performance for lights and air conditioning units, lack of proper setpoints or guidelines for mixed-mode operation, lack of system documentation and high nocturnal loads. These issues could be easily resolved by improved leadership and application of basic energy management principles at an organisation level, with no additional costs. Larger buildings, on the other hand, encounter a higher frequency of issues related to HVAC and lighting systems. The most common issues in larger buildings relate to a lack of commissioning; improper operation of systems is commonly identified. The increased number of lighting control issues is partially related to the fact that larger buildings have larger floor plans and bigger zones, so are more likely to have areas which are improperly controlled, where circuits should be separated or where automation does not work properly.

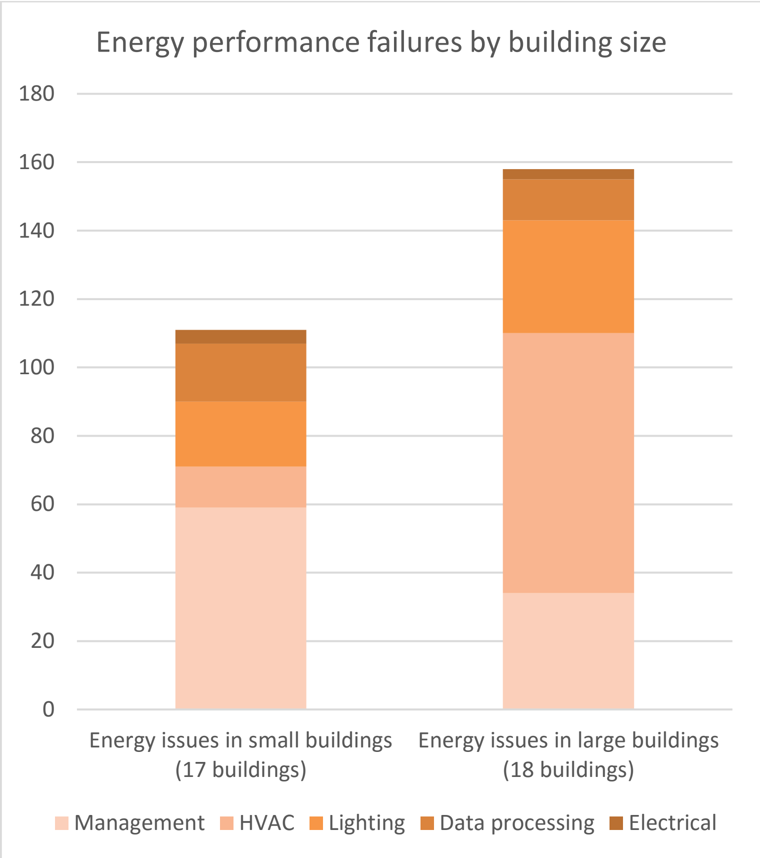

Figure 2 - Number of building energy performance failures encountered in large and small buildings

While 9 energy system failure modes (representing 64 occurrences) were deemed to be primarily due to the building design and construction (D&C), as shown in Table 4, the other 29 failure modes (205 occurrences) were primarily due to the operation and maintenance (O&M) procedures of the building, shown in Table 5. The methods for correcting failures also vary widely; while most failure modes resulting from D&C require building retrofits to resolve them, only a single O&M failure mode requires a retrofit procedure (installation of capacitors to correct power factors). Other failures can be resolved through commissioning, better maintenance and operational changes.

It is noted that many of the design failures related to server rooms in smaller buildings. While large data centres are often found to be professionally designed and well-operated, smaller server rooms are significant energy consumers which may grow organically over time and often have no professional design, leaving significant opportunities for correction of the poor layouts and other characteristics.

Some common failure modes may not affect the total energy consumption (kWh), but will have a significant impact on the total annual cost of operation of the building. This includes power factor adjustment and energy contract optimisation – a zero-cost measure which showed large savings in many of the cases analysed.

Table 4 - Energy-related failure modes caused by inadequate design and construction

Area	**Failure mode**	**Resolution**	**Frequency (sample=33)**
Data processing	Server rooms layouts are not optimised	Retrofit	10
	Server rooms are not properly insulated or have solar gains	Retrofit	6
Electrical	Unbalanced electrical loads between phases	Maintenance	2
HVAC	No variable speed drive or no adequate control on chilled water circuits	Retrofit	6
	Overuse of cooling tower systems due to poor design or incremental expansion	Retrofit	5
	Oversized pump motors	Retrofit	2
Lighting	Lighting systems left switched on due to lack of automation	Retrofit	15
	No separation of lighting circuits means lights are left on unnecessarily	Retrofit	14
	Excess illumination provision	Maintenance	4

Table 5 – Energy-related failure modes caused by inadequate operations and maintenance

Area	**Failure mode**	**Resolution**	**Frequency (sample=33)**
Data processing	Oversized cooling systems for UPS and server areas; backups work full-time instead of as back-ups	Operations	4
	Server room setpoints are lower than recommended levels	Operations	7
	Bypass mode on UPS is deactivated	Operations	2
Electrical	Power factor outside recommended limits	Retrofit	5
HVAC	Chiller operational parameters (setpoints and control schedules) are not optimised	Commissioning	13
	Fancoils, ventilation and exhaust systems are left switched on outside usage hours or surplus to requirements	Operations	12
	VFDs are not properly set or are operating at fixed speeds	Commissioning	10
	Overuse of cooling tower systems due to inadequate operation and fixed-speed drives	Maintenance	9
	Chillers operate outside required operational hours	Operations	8
	Setpoints for cooling are not optimised and can be increased	Operations	6
	Damaged or degraded insulation on chilled water pipes, refrigerant circuits or cool air ducts	Maintenance	5
	BMS permits visualisation of trends, but this functionality is not used	Operations	4
	Thermoacculumulation (ice) tanks are installed but not programmed for use or not optimised	Commissioning	2
	Air conditioning system setup means most systems work through the night or weekend as no part-load system	Commissioning	2
	Leaks from chilled water system	Maintenance	1
	Significant openings in building fabric of conditioned areas, for example around window a/c units	Maintenance	3
Lighting	Lighting system automation installed but switched off, not fully used or incorrectly programmed	Commissioning	7
	Daylighting use not optimised	User	8
	Lighting systems left switched on due to poor manual control	User	4

Management	Inadequate metering of energy supplies or documentation of consumption	Operations	11
	High nocturnal loads, unaccounted for. For example, office equipment left switched on outside operational hours	Operations	14
	Procurement of key equipment, such as split air conditioning units, with low efficiency ratings	User	20
	Energy contracts are not optimised	User	15
	Lack of adequate system documentation	Operations	9
	Natural lighting and/or mixed-mode air conditioning used without proper guidance, setpoints or environmental considerations	User	16
	Inefficient use of parking bays in low occupation	Operations	2
	Building use of space is not optimised - low occupation without corresponding energy benefits	User	4
	Activate the night cooling system which was designed and installed, but not used	Commissioning	1
	External shading is not properly used	Operations	1

Analyses of user satisfaction

Of the four buildings which received BUS surveys, three were large buildings (30,000m² or over) and the fourth was a medium-sized building (4,600m²). One of the large buildings, unusually, operates under natural ventilation mode, while the others all use chilled water systems with fancoils. They cover a range of ages; while one has only been operational since 2010, the others are older and the building services are correspondingly antiquated.

Table 6 - Characteristics of buildings in which BUS studies were carried out

Building reference	**Key characteristics observed during the site visit**	**IEQ issues identified, by impact**		
		High	**Medium**	**Low**
29	Historic building. Naturally ventilated, only some rooms are conditioned.	1	3	0
30	Old building systems but high-performance maintenance team	0	0	3
31	New building and high-performance maintenance team	0	0	2
32	Old systems and ineffective maintenance	1	1	3

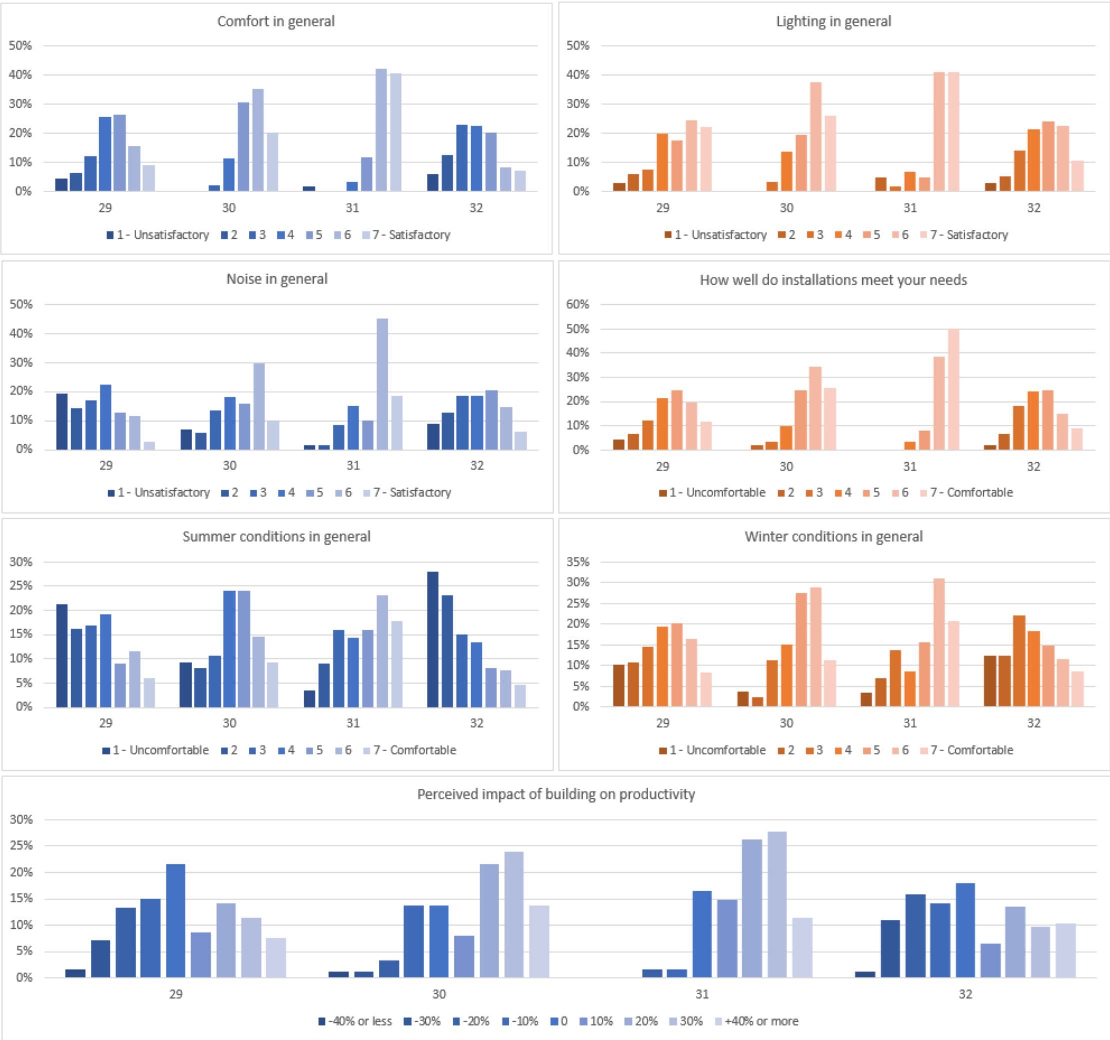

Figure 3 - Selected results of BUS surveys in four buildings

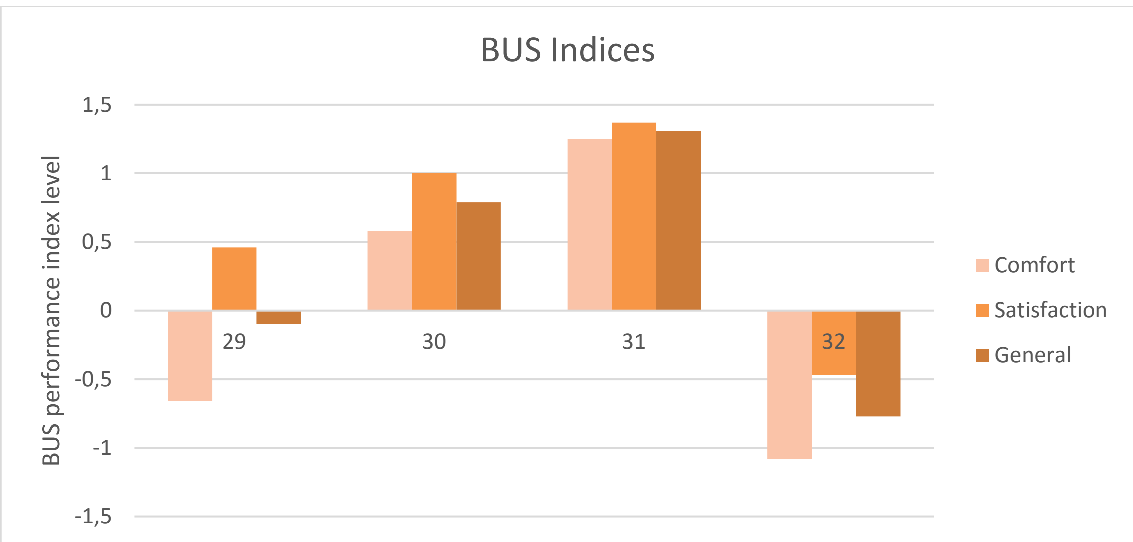

Figure 4 - Aggregated BUS indices for user satisfaction

The BUS questionnaire collects responses to 48 individual questions. The raw responses should ideally be compared to larger datasets to draw useful conclusions regarding the performance of a building. However, as no dataset exists for BUS surveys on buildings in Brazil, the buildings are compared amongst themselves to draw some conclusions.

The responses to several of these questions are shown in Figure 3, which clearly demonstrates difference in the occupant satisfaction amongst the buildings. Figure 4 shows aggregated performance indices developed by BUS for overall comfort, user satisfaction and general building conditions in the BUS Summary Index.

Buildings 30 and 31 have high performance generally, with building 31 showing exceptionally high ratings in nearly all areas. During the building surveys, it was noted that both buildings have dedicated and effective maintenance teams and as can be seen from Table 6, neither registered any high- or medium-impact failures related to environmental quality in the building. There is a significant difference in the efficiency and performance of the building systems; building 31 has state-of-the-art, high-end systems, was recently completed and has LEED certification. Building 30 was built in 1999, before sustainability certifications and energy efficiency became significant design considerations in Brazil. The systems are old and less efficient; retrofit of some systems is likely to be required in the coming years. Despite this, the occupant satisfaction of the two well-operated buildings is very similar in several areas. Importantly, both buildings have very positive impacts on the perceived productivity of the occupants.

Building 29 is a historical building which is largely unconditioned and relies on natural ventilation and large window areas to keep a 36,000m^2 office functioning effectively. The building has poor performance related to noise, from open windows in a noisy environment in the city centre - the building survey raised the challenges of use of natural ventilation in this environment as the most critical performance issue related to environmental quality. Although there is some discomfort in the summer, this building does not perform as poorly as might be expected, given the challenges of operating an office without air conditioning in an urban centre in a warm climate. The building surveys showed this office to have very low levels of specific energy consumption, compared to its peers. Although the satisfaction index is not as high as in buildings 30 and 31, it is still positive.

The building services in building 32 have similar technical specifications to those in building 30 but, in this case, clear failures are seen in design, maintenance and retrofit over the years of operation of the building. One issue noted in the survey is that the building passed through incremental expansions over several years, without ever undergoing a full redesign. The HVAC systems now function without effective external air supplies, with no control of chilled water flows, with unbalanced distribution from air handling units, with thermostats in incorrect locations and with no local controls. The overall impact of these failures is a system that uses a great deal of energy to produce uncomfortable conditions for the users.

Through direct observation and interviews with building managers, the energy audits independently identified many of the main issues raised in the user satisfaction surveys, and provided a technical background which allows for the identification of solutions to these problems. There are some issues which are clearly important to users which were not covered in the energy audits, such as internal noise sources (from colleagues or other areas in the building), and which may not be directly linked to the performance of the building services.

Discussion

Design and operation

These results make it clear that effective O&M in buildings is the single most important factor for good performance, regardless of size, age or type of building systems. In a real estate market which depends heavily on outsourced maintenance, the supervision of the contracts and performance of maintenance providers is an essential aspect for guaranteeing performance. The facilities managers and operational teams of the occupants must lead the identification and implementation of improvements and ensure the quality of the maintenance provision. The data gathered on the type of maintenance contract was limited, and insufficient to show strong correlations with performance. Both in-house and outsourced operations and maintenance teams can be dedicated and proactive, or fail to meet even basic health and safety requirements. The audits and surveys carried out here showed the results of poor O&M practices, but did not study the reasons for these levels of performance.

Where full user satisfaction analyses were carried out, good building design was seen to influence user satisfaction, but the quality of the ongoing operation and maintenance of the building had a significantly larger impact.

A range of building design issues should be easy to identify and correct during planned refurbishments and especially in the construction of new buildings. Although some of these issues are caused by incorrect design parameters, it is important to note that others were caused by refurbishments or system retrofits which were carried out without proper design or full evaluation of performance criteria.

Strategies for building performance improvement

From the results shown here, it appears that small buildings could use simple checklists or even automated systems for identifying performance failures and would mostly benefit from improved maintenance procedures, training of in-house teams and approval of energy management strategies. As users already have very high levels of control, these buildings will have less need of automation for energy efficiency, and complex systems should generally be avoided as this reduces the possible number of performance failures. High-quality commissioning professionals are expensive and verifying their work may be beyond the capabilities of the operational teams of small buildings. (An example of this type of procedure has recently been developed for small commercial buildings in six locations in the USA [54].)

Large buildings are more likely to require commissioning, as they use larger and more complex systems. In every single case studied, newer buildings require fine-tuning and adjustments to their operational parameters to optimise their operations (this includes those with LEED certifications). This is despite the fact that buildings were seen to use simpler HVAC systems than equivalent office buildings in developed economies. In these buildings, the investment in professional commissioning services is likely to produce energy savings commensurate with the cost of the service, as well as improved internal conditions. Older large buildings which are well-operated would benefit from investments in building automation to improve efficiency, while there are a few older buildings which have inadequate maintenance procedures and basic operational errors; these buildings are the worst performers and require drastic interventions to return to adequate performance levels.

These results are applicable specifically to office buildings in Brazil, but similar performance issues are likely to be replicated in performance issues of commercial buildings in many other emerging markets and warm climates.

Building failures and comfort levels

Only four buildings received BUS assessments; although this small sample size means that these results may not be statistically significant across the building stock, these buildings illustrate issues encountered in many other office buildings and as such represent useful case studies for extrapolating preliminary conclusions.

Although each building which received a BUS assessment had been identified as showing some IEQ failures during the initial survey, the classification of the severity of these issues was key to predicting the impact on occupant satisfaction. Buildings 29 and 32, each of which had noted one high impact IEQ issue, as well as at least one medium impact issue, both had significant proportions of occupants reporting discomfort and lower productivity levels. Building 29 identified underused natural ventilation, external noise and poor shading, while Building 32 noted uncontrolled and unbalanced cooling systems with no external air supply. The building audits did not capture all of the issues raised in the BUS surveys; for example, noise from poorly designed internal partitions was a key issue that did not appear in the energy audits.

One of the most striking results is that although the overall comfort ratings are generally close to the overall satisfaction levels, this relationship does not hold true for Building 29, which has a positive satisfaction rating despite its negative comfort levels. An analysis of the comments provided in the BUS entry forms suggests that this may have to do with the architecture (high ceilings and large windows) and the pride people feel in working in a highly iconic building. Neither of these factors would appear in an energy audit, but they contribute significantly to user satisfaction.

Occupant satisfaction levels in Building 31 are extremely high in nearly all categories (a comparison with a dataset of BUS studies in Australian buildings would put it in the 97th percentile for comfort overall and give the highest recorded result for perceived productivity). This building, while also iconic and a major landmark, is brand new and many of the people now working there would have moved from inferior conditions in their previous workspaces. It would be informative to repeat this study after a further 2-3 years of occupation, to see if these levels of satisfaction have been maintained. The only IEQ issues raised in the energy audit were related to minor issues of control of external air and indoor flow rates – after receiving the survey, the maintenance team aimed to correct both within months.

Conclusions

Environmental quality and energy performance benchmarking

An evaluation of building energy performance typically starts with a benchmarking exercise, to compare measured consumption with the performance which would be expected from similar buildings under similar conditions. However, 85% of the office buildings studied show some sort of failure in the provision of environmental quality to the users, making it clear that an evaluation of environmental quality should be incorporated into any effective benchmarking scheme. Buildings which do not meet minimum environmental performance criteria may use less energy than other, similar buildings (for example, if office areas are illuminated to 250 lux instead of 500 lux), but this does not demonstrate greater efficiency in the provision of services in a building.

Retrofit strategies for energy efficiency must consider the issues faced in guaranteeing the performance of existing buildings. A building which is not capable of providing thermal comfort to its users is unlikely to provide the estimated level of savings from the installation of a new chiller, for example.

Performance levels

The performance gap between predicted and measured energy consumption is undoubtedly partly explained by the failures in building systems. These have a range of causes and effects, but are mostly linked to inadequate operation; optimising the operation of buildings is likely to remove a significant proportion of the difference between predictions or benchmarks and actual performance.

Even in less complex buildings, a lack of management leads to severe performance failures. The buildings in this dataset are all office buildings from an emerging economy; as such they have relatively simple building services but also have a less highly-trained professionals available for operations and maintenance work. This situation is likely to be replicated across a range of developing countries in warm climates and requires a focus on training and energy management procedures, to improve indoor environmental quality and capitalise on the low- and zero-cost opportunities for saving significant quantities of energy in the built environment.

Further work

This study indicates that it may be possible to identify many of the main issues related to occupant satisfaction during a short building audit and interview with key personnel. A larger sample of buildings subjected to full IEQ questionnaire analyses would produce results which could produce stronger correlations between the identified performance failures and reported comfort issues. This, in turn, might be used to refine building performance analysis methodologies without requiring the application of expensive questionnaires.

There is a clear need for further work to link building energy performance to the levels of O&M service provided in the buildings. This can be through evaluations on the levels of resourcing for O&M (in terms of cost, expertise and contract scope), but also through evaluations of response time and effectiveness in correcting performance failures. Links to building administrators and processes for approving repairs, updates and new equipment installations are essentially management issues, but as this paper has shown, management failures can lead to building performance failures with significant impacts on energy performance as well as comfort, and hence productivity and wellbeing of users.

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