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ASSESSING THE SMARTNESS OF BUILDINGS

INTRODUCTION

The concept of "smart" building has risen up in the last few decades. Awareness of the importance of developing smart buildings is increasing. Higher competitive pressures force owners and developers to design and construct buildings that can be considered smart in terms of energy efficiency, occupant comfort, development and operating costs. Furthermore the adaptation to climate change is emerging as one of the main requirements for buildings in satisfying environmental performance (Love and Bullend, 2009), hence promoting "smart" solutions. Also, the concept of smart is an important part of the sustainability movement. Indeed, a green building incorporates building plans for least energy consumption and minimum life-cycle costs, in addition to objectives such as minimum environmental impact, the production, transportation and use of sustainable materials, minimum waste, and minimum maintenance (Tsai et al., 2014). The concept of smart is receiving a great of attention worldwide not only in relation of the sustainability issue, but also because it makes use of interconnected technologies and because it generates a high level of comfort for the occupants (GhaffarianHoseini et al., 2013). Owners and developers seek to achieve and document high performance buildings in order to gain competitive advantage; designers are promoting their services based on the performance of their projects; and tenants and occupants are interested in their buildings' performance (Jarvis, 2009).

Smart buildings involve the usage of design solutions, technology and processes to develop facilities that are comfortable and safe for their occupants while at the same time economical for their owners (Katz and Skopek, 2009). The adjective "intelligent" has been often used instead of "smart" (Wong and Li, 2009). Smart buildings create an environment that maximizes the efficiency of building services, ensuring effective resource management with minimum lite-cycle costs (Perumal et al., 2010).

This objective is reached since these buildings “decide” the most efficient way to provide with an appropriate environment for its occupants (Loveday et al., 1997). In particular the deployment of ICT solutions for home automation, heating and cooling and facility management allows for more productive and cost effective ownership (So et al., 1999), such as through users comfort solutions and the optimization of energy consumption (Nguyen and Aiello, 2013).The goal is to achieve the optimal combination of comfort and energy consumption (Wang et al., 2012), and therefore improve the performance of the building. The complexity of buildings is more and more increasing, thus an integrated system to monitor buildings functionalities, such as energy consumption, is required (Marinakis et al., 2013). However passive aspects too, appear to be crucial for the enhancement of smartness as demonstrated by Ochoa and Capeluto (2008). The Smartness is considered in all the phases of a construction project, including design, construction, and operation.

Many definitions of “smart” are cited in the context of building projects, but a standard definition does not exist so far. Researchers and practitioners usually focus on one or few aspects and there is a lack of comprehensive classification of the most common fields associated with smart buildings. This lack of standard definition can make it difficult to measure the smartness of a building. The objective of the research presented in this paper is to capture the perspective of professionals about smart buildings. After the pertinent literature is examined, three different domains are identified, namely, economic issues, energy issues, and comfort issues. A large number of construction managers are surveyed for their opinions about these issues. Based on the results of the survey, a Smartness Index (SI) is developed, and future research directions are proposed.

ISSUES IN SMART BUILDINGS

Buildings are increasingly expected to meet higher and potentially more complex levels of performance because the demands of building owners and occupants are changing. While requiring adequate physical space, owners and occupants of a building also require the building to perform well in terms of cost and comfort. Moreover, buildings should use minimum energy, and yet be economical to build, operate and maintain (Kolokotsa et al., 2011). In other words, buildings are expected to be “smarter” and there is a whole range of design, managerial and organizational issues that need to be addressed, with regard to reliability, operational management, and performance to meet users’ requirements (Shabha, 2006). Smart buildings are becoming more attractive and viable to potential inhabitants by producing energy savings while meeting comfort requirements (Zhang et al., 2013). In a smart building, different information such as temperature, humidity, air flow, light, and sound can be collected from sensors and transferred to the building control system in order to track the conditions and the human behavior, and in turn achieve savings in terms of energy consumption with an increased level of comfort (Kwon et al., 2014). Cole and Brown (2009) propose a set of key attributes for smart buildings:

- Automated buildings: automated systems that control the building services.
- Digital buildings: integrated, centrally managed information and communication structures.
- Intelligent space management: capability to respond to rapid changes in the size and in the structures of organizations and work practices.
- Passive intelligence: perceptive design strategies, to positively influence environmental performance and thereby reducing or replacing unnecessary systems.
- Organizational intelligence: strategic plans that integrate organizational needs with building capability and capacity.

Recent years have seen a variety of products developed and introduced to the market to enhance building performance, and to meet a variety of human needs. They are designed to provide mobility in communication, facility management, environmental control, fire protection, and security. These innovative technologies can be considered for the improvement of energy efficiency and indoor comfort. In particular, the innovative shading, the improvement of the building fabric, the use of renewables, the incorporation of high-efficiency heating and cooling equipment, and the use of advanced sensors and monitoring systems have been prevalent (Kolokotsa et al., 2011). The idea of Smart Building originated from the concept of smart automation which provides benefits to end users, including lower energy costs, provision of comfort, and increased security (Pedrasa et al., 2010). According to Moreno-Munoz et al. (2011), smart buildings can deal with the energy efficiency issue by integrating smart technology and solutions, while enhancing the quality of life.

It has become widely accepted that measures in the building *modus operandi* can bring important performance improvements and therefore enhance the smartness of a building. For example, Lu et al. (2009) argue that the most important aspect associated with smart buildings is the ability to measure and monitor their service systems. Yang and Peng (2001) propose measuring the performance of a building by looking into its organizational flexibility, technological adaptability, individual comfort, and environmental performance. Gonzàlez et al. (2011) propose an energy efficiency index that is basically the ratio between the performance (in terms of energy consumption or CO_2 emissions) of an actual building and the performance of a reference building. Chen et al. (2006) suggest three different assessment methods for measuring building performance, including rating methods based on indicators associated with design, operation, and simulations. Wong, et al. (2008) propose eight building control systems in a typical smart building:

- Integrated building management system for overall monitoring of the building
- Heating, ventilation, and air-conditioning control system for comfort control and the quality of the indoor air
- Addressable fire detection and alarm system for fire prevention and annunciation
- Telecom and data system for communication network
- Security monitoring and access system for surveillance and access control

- Smart/energy efficient lift system
- Digital addressable lighting control for light design
- Computerized maintenance management system

Chwieduk (2003) emphasizes the performance of solar-power systems and heat pumps, waste sorting, the re-utilization of wastes, water treatment, water-saving equipment, use of rain water, and re-use of waste water, whereas Wong and Jan (2003) propose performance measures in spatial comfort, indoor air quality, visual comfort, thermal comfort, and acoustic comfort; Morsy (2007) states that psychological aspects can influence building users' comfort and that smart buildings' performance in adapting to the psychological needs of the occupants is important.

According to Kleissl and Agarwal (2010), buildings are composed of subsystems associated with airflow, water, safety, access, and security that run together and share information. Since all subsystems work together in a building, the sharing of information between subsystems is critical (Jiang et al., 2009). Therefore the key requirement for consistent and efficient monitoring in a smart building is that all sensors be addressable over a communication network (Schor et al., 2009), since such a network supports the efficient collection of sensed information and its dissemination to consumer devices (Familiar et al., 2012). The Building Intelligence Quotient (BIQ) proposed by the Continental Automated Building Association (CABA) makes use of communication systems, building automation, annunciation, security and control systems, facility management applications, and building structures and systems.

Several building performance evaluation tools exist, such as The Building Research Establishment Environmental Assessment Method (BREEAM,) in the UK and Leadership in Energy and Environmental Design (LEED, 2008) in the US, but they basically focus on the many sustainability issues (Ding, 2008). Smartness can be considered to be part of the sustainability effort, but requires specialized evaluation. Table 1 summarizes the three different domains related to a smart building (i.e., economic, energy, and occupant comfort issues) with the associated variables identified through the analysis of the current literature.

Tools	Domains	Variables	Sources
Communication network, automation technologies, and materials/equipment	**Economic Issues**	Planning and design costs	Alwaer and Clements-Croome 2010; Brown and Southworth 2006
		Construction costs	Alwaer and Clements-Croome, 2010
		Operation and maintenance costs	Kolokotsa et al. 2011; Wong, Li, and Lai 2008; Alwaer and Clements-Croome 2010
		Sustainability costs	Wang et al. 2012; Kolokotsa et al. 2011
	Energy Issues	Heating systems	Wu and Noy 2010; Wong, Li and Lai 2008; Kolokotsa et al. 2011; Chwieduk 2003; LEED, 2008
		Cooling systems	Wu and Noy 2010; Kolokotsa et al. 2011
		Lighting systems	Wu and Noy 2010; Wang et al. 2012; Eang and Priyarsdasini 2008; Wong, Li, and Lai 2008; Wong and Jan 2003; LEED, 2008
		Water systems	Chwieduk 2003; Kleissl and Agarwal 2004
	Occupant comfort	Temperature	Doukas et al. 2007; Wang et al. 2012; Eang and Priyarsdasini, 2008
		Humidity	Doukas et al.2007
		Air quality	Doukas et al. 2007; Wang et al. 2012; Eang and Priyarsdasini 2008; Wong and Jan 2003
		Acoustic comfort	Wong and Jan 2003
		Functionality	Yang and Peng 2001
		Psychological aspects	Morsy 2007
		Security	Doukas et al. 2007; Wong, Li, and Lai 2008; Kleissl and Agarwal 2004
		Fire protection	Doukas et al. 2007; Wong, Li, and Lai 2008

Table 1. Domains and the associated variables

Economic Issues

A smart building might be considered as composed of a complex system of three inter-related elements: products (structure, equipment, facilities, materials), people (users, owners, occupants), and processes (construction, facility management, maintenance) (Alwaer and Clements-Croome, 2010). An essential requirement is the economic viability. Wagner et al. (2014) compare the cost of conventional buildings with new ones built through new technologies: their results show the additional initial costs required to enhance the efficiency is less than 5% of the cost of conventional buildings. Therefore, the challenge is to set up a team so that every member's responsibilities align with the same objectives and all these responsibilities collectively appear able to militate for success (Elliott, 2009). In this process, design, construction, and facility management are equally important (Clement-Croome, 2004). A smart building must be able to respond to individual, organizational and environmental requirements and to cope with changes while keeping costs down. Mohammed et al. (2014) state that there is a strong need for a comprehensive techno-economic evaluation in the assessment of a building. In this regard, Ling and Gunawansa (2011) suggest considering life-cycle costs instead of focusing on upfront costs. In particular, attention should be paid to the cost of investment, in addition to the reduction of the cost of energy, maintenance, cleaning, replacement, and end-of-life expenses (Debacker et al., 2013). It is also believed that a smart building should be able to learn and adjust its performance based on the information obtained from its occupants and the environment (Yang and Peng, 2001).

Energy Issues

Buildings are responsible for a large percentage of energy consumption and greenhouse emissions as they consume around 40% of the total end-use energy all over the world and over 90% in some urban areas such as Hong Kong (Xue et al., 21014). Since energy remains invisible to end-users, it is very important to influence the users' energy management in an effective way (Aune et al., 2009). The energy issue is one of the domains where researchers have devoted more effort in the last years forced by legal restrictions and increasing economic burden (Figueiredo and Martins, 2010). Building energy performance is a critical aspect in the assessment of smartness (Crosbie et al., 2010). Most of the energy used is for heating, cooling and lighting in both commercial and residential buildings (Wu and

Noy, 2010). Impacts of high energy consumption on the environment are gaining importance as society recognizes the seriousness of this issue (Boussabaine and Vakili-Ardebili, 2010).

In the future, the main concern is not related to how to produce the energy that is needed, but to reduce energy consumption and to mitigate the effects of high consumption on the environment and health (Gonzàlez et al., 2011). Building can help improving energy performance (Xue et al., 2014) and in addition to energy-efficient design strategies, increasingly common building automation systems can help respond to these needs. Moreover the use of technology adds value to the building and there is a widespread interest in the inclusion of smart technology in a new building (Peteresen et al., 2001). A smart building’s automation system usually consists of several subsystems such as HVAC control, security and access control, fire security, building transportation control, etc. that contribute to the achievement of higher energy efficiency, higher levels of comfort, and lower costs (Doukas et al. 2007). In particular, the HVAC system can be considered to be a critical aspect in the management of energy in a smart building (Missaoui, et al., 2014). The energy assessment is then crucial for owners and tenants since it can provide with information regarding how much energy being consumed and consequently it should be a motivation to identifying savings opportunities. Hence, making a more smart use of energy in buildings can fundamentally contribute to energy and cost savings (Nguyen and Aiello, 2013) and smart initiatives in this field generate benefits in terms of energy costs and carbon emissions from the building sector (Wang et al., 2012)

Occupant Comfort Issues

Apart from energy and economic-related aspects, occupant comfort is a decisive factor in assessing the performance of a building (Wagner et al., 2014, Fathian and Akhvan 2006). In this context, smart buildings place greater emphasis on the adaptability and the management of space, providing a more user-oriented approach (Drewer and Gann, 1994). Any technological intervention should not only be cost-effective, but also be acceptable to the end-users in terms of providing a comfortable, and healthy indoor quality environment (Hall et al., 2013). For this reason, in addition to energy conservation, Kofler et al. (2012) propose different domains of interest for smartness, namely resource information, exterior influence, building information, actor information, process information, and comfort information. According to Wang et al. (2012), three basic factors – thermal comfort, visual comfort and indoor air quality – measure the quality of living in a building environment. Temperature, illumination level, and CO2 concentration are three main indexes for thermal comfort, visual comfort and air quality, respectively. Eang and Priyarsdasini (2008) as well, indicate thermal comfort, illumination, fresh air ventilation, and indoor air quality as environmental parameters that should be taken into account. Wu and Noy (2010) propose evaluating comfort indexes that have significant influence on people's well-being in the building by installing sensors to collect data about indoor physical parameters. From a social perspective, low levels of comfort (in particular in relation to high or low temperature) cause distress and even health issues for the occupants. In a work environment, higher occupant satisfactions have been shown to be directly associated with productivity (Holopainen et al., 2014). The reduction of the power consumption requires continuous monitoring of various environmental parameters inside and outside the building. In particular the temperature has significance for economic aspects, and in a wider context, for the sustainability (Tolman, and Parkkila, 2009). The methodology proposed by Doukas et al. (2007) includes both indoor and outdoor sensors (for the measurement of temperature, humidity, air quality, and luminance), controllers (e.g., switches, diaphragms, valves, and actuators) and databases (that record all the information). Chappells (2011) reviews different understandings of comfort and well-being and the approaches to intelligent building practice they inspire.

However, a successful smart building cannot be just a collection of automation features. It has to be the product of a design process that incorporates intelligence in all its stages (Ochoa and

Capeluto, 2008). Moreover the system's intelligence is feasible only if the information exchange among the various functional units is reliable and trustable (Wang and Khanna, 2011). The smartness of a building is related to its capability to ensure safety, comfort, effectiveness and efficiency to occupants (So et al., 1999).

RESEARCH METHODOLOGY

The research has been conducted in four steps.

- First, the different domains and constituent variables associated with the smartness of a building has been identified (Table 1) by reviewing the literature.
- Second, based on the domains and their variables, a survey questionnaire has been designed to seek the opinions of professionals on these issues. After some general questions about their professional experience, the respondents have been asked to rate the importance of the tools that can be used to enhance the smartness of a building, the importance of the different domains and the importance of the variables associated with the domains. For all statements, a Likert-scale scoring system was used, where 1 = Not important, 2 = Moderately important, 3 = Important, 4 = Very important, and 5 = Extremely important.
- Third, the survey was administered to a group of professionals and practitioners who are members of the Construction Management Association of America (CMAA), an organization formed in 1982 that is dedicated to the interest of professional construction management. CMAA represents construction management professionals in North America regardless of whether they work for contractors, designers, or owners. Construction management professionals routinely deal with the economic, energy, and occupant comfort issues that are investigated in this study relative to smart buildings. Therefore construction management professionals constitute the population of choice for such an investigation as they represent both

the demand side (owners) and supply side (contractors and designers) of the construction activity. All the identified respondents received an email presenting the research group and the aims of the study. The email provided a link to the survey instrument. As soon as the respondents completed the questionnaire, the results were sent to the researchers for analysis.

- Fourth, the data collected were studied, the findings were statistically analyzed in the light of the existing literature, and conclusions were drawn about the current perceptions of the smartness of buildings. The data were tested for convergent validity in order to check if the variables actually converge to measure the same construct (Lim et al., 2011). Also, the collected data were based on a 1 to 5 Likert scale, and were not normally distributed. Indeed, Gaito (1980), states that a Likert scale is ordinal to the extent that one cannot guarantee the distance between 1 and 2 is actually the same as between 4 and 5. Therefore a non-parametric test was used to perform statistical analysis. In particular, The Kruskal-Wallis test was used: this test is a non-parametric method that investigates whether samples originate from the same distribution. In case of significant results, at least one of the samples is different from the others (Kruskal and Wallis, 1952). The Kruskal-Wallis statistic is presented in Equation 1.

$$K = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_i - \bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}(r_{ij} - \bar{r})^2} \tag{1}$$

where:

- n_j is the number of observations in group i
- r_{ij} is the rank (among all observations) of observation j from group i
- N is the total number of observations across all groups
- $\bar{r}_i = \frac{\sum_{j=1}^{n_i} r_{ij}}{n_i}$
- $\bar{r} = \frac{1}{2}(N+1)$ is the average of all the r_{ij}

The Kruskal-Wallis statistic tests the null hypothesis that the populations have identical medians. If the test has a p-value lower than the significance level (usually 5%), the null hypothesis can be rejected in favor of the alternative hypothesis of at least one difference among the groups under analysis.

- Finally, based on this information, a smartness index (SI) has been developed. SI has been calculated as the mean value of the importance ascribed by the respondents to each domain and sub-domains. Then, domains and sub-domains have been weighted through a normalization.

FINDINGS AND DISCUSSION

The questionnaire was sent to 1,600 professionals that are members of CMAA; 120 responded, yielding a rate of response of 7.5%. Any size of company is represented in the sample evidenced by 41 having fewer than 1,000 employees, 32 with 1,000 to 10,000 employees, and 43 with more than 10,000 employees.

Figure 1 shows that most of the respondents had 20 and 35 years of experience in construction. This means that the sample is made up of very skilled professionals, and therefore the answers can be considered as reliable.

According to the information in Figure 2, the majority of the professionals are constructors or designers, with only 19 owners. Construction management services are often provided by constructors and designers. It is not surprising to see only a few owners among the respondents because of the low number of owners that are members to the CMAA.

The rate of response of 7.5% may seem low at first glance, but actually it is quite respectable in exploratory research in construction. The 120 responses constitute a large enough sample that allows statistical inference and leads to reasonable conclusions, particularly since large/medium/small firms, and contractors/designers/owners are suitably represented by respondents with extensive experience

(20 to 35 years in the industry). One can state that the respondents represent quite well a good cross-section of the building construction industry.

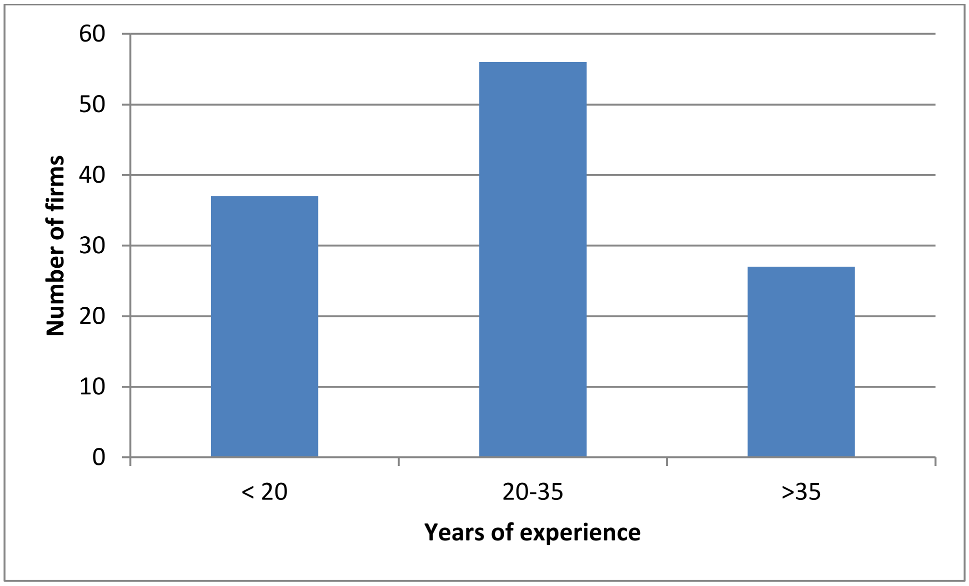

Figure 1. Number of years of experience of the respondents

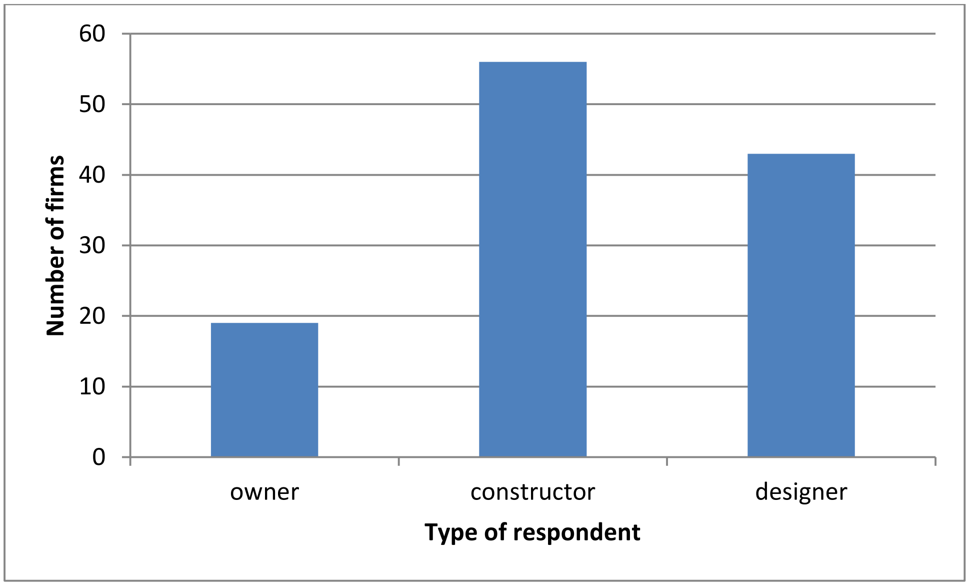

Figure 2. Role of the respondents

Table 2 shows the Cronbach's Alpha coefficient, computed in order to check the validity of the analysis that is performed. This coefficient is a measure of internal consistency that assesses how reliably surveys are designed. It ranges between 0 and 1, where higher values indicate higher consistency. A threshold of 0.7 indicates that the items actually evaluate the same construct (Churchill, 1979).

Domains and Variables	Mean scores			Kruskall-Wallis p-value	Normalized weights
	Owner	Constructor	Designer		
Economic Issues (X)	4.25	4.17	4.05	0.549	0.33
Planning and design costs (x_1)	4.50	4.57	4.38	0.878	0.28
Construction costs (x_2)	3.55	3.47	3.78	0.176	0.22
Operation and maintenance costs (x_3)	4.40	4.16	4.23	0.284	0.26
Sustainability costs (x_4)	4.10	3.83	3.92	0.281	0.24
Energy Issues (Y)	4.40	4.38	4.40	0.746	0.35
Heating system (y_1)	4.60	4.24	4.40	0.17	0.26
Cooling system (y_2)	4.60	4.37	4.54	**0.036**	0.27
Lighting system (y_3)	4.40	4.04	4.21	**0.032**	0.25
Water system (y_4)	3.8	3.32	3.76	0.082	0.21
Occupant Comfort Issues (Z)	4.25	3.81	3.98	0.133	0.32
Temperature (z_1)	4,15	4.32	4.23	0.847	0.12
Humidity (z_2)	3.70	3.71	3.85	0.548	0.12
Air quality (z_3)	4.00	4.17	4.26	0.585	0.14
Acoustic comfort (z_4)	3.5	3.49	3.71	0.464	0.12
Functionality (z_5)	4.05	3.75	4.00	0.253	0.14
Psychological aspects (z_6)	3.65	3.07	3.50	0.056	0.11
Security (z_7)	3.15	3.58	3.45	0.275	0.11
Fire protection (z_8)	3.70	4.04	3.85	0.272	0.13

Table 2. Cronbach's Alpha Coefficients

The results show that all the coefficients are higher than 0.8, meaning that the proposed questionnaire is properly developed to capture the perceptions of professionals about smart building issues.

Table 3 shows the results of the Kruskal-Wallis test performed on the different professionals who responded to the survey. The results highlight that owners, constructors and designers have the same opinions about life-cycle costs and occupant comfort, but not about energy issues, particularly with respect to cooling and lighting systems, variables that are considered to be less important by constructors. Constructors typically receive plans and specifications prepared by designers and are bound by the materials and methods set by designers. As such, constructors have only limited input into smartness-related decisions. However, designers and construction managers representing owners can play a vital role in the development of smart buildings, in particular in the definition of problems and the research for solutions.

Domains and Variables	Mean scores			Kruskall-Wallis p-value
	< 20 years of experience	20-35 years of experience	> 35 years of experience	
Economic Issues (X)	4.27	4.11	4.00	0.474
Planning and design costs (x_1)	4.59	4.41	4.50	0.587
Construction costs (x_2)	3.62	3.75	3.18	0.370
Operation and maintenance costs (x_3)	4.19	4.32	4.09	0.366
Sustainability costs (x_4)	4.11	3.88	3.68	0.129
Energy Issues (Y)	4.57	4.36	4.18	**0.049**
Heating system (y_1)	4.62	4.30	4.09	**0.016**
Cooling system (y_2)	4.73	4.41	4.23	**0.016**
Lighting system (y_3)	4.24	4.27	3.77	**0.043**
Water system (y_4)	3.78	3.63	3.05	**0.011**
Occupant Comfort Issues(Z)	4.05	3.95	3.77	0.474
Temperature (z_1)	4.35	4.29	4.05	0.246
Humidity (z_2)	3.73	3.82	3.68	0.664
Air quality (z_3)	4.16	4.11	4.36	0.433
Acoustic comfort (z_4)	3.49	3.61	3.64	0.564
Functionality (z_5)	3.92	3.98	3.64	0.252
Psychological aspects (z_6)	3.41	3.38	3.09	0.375
Security (z_7)	3.43	3.45	3.55	0.909
Fire protection (z_8)	3.81	3.93	4.05	0.717

Table 3. Results of Statistical Analyses

The years of experience (Table 4) show significant differences in the energy performance domain. The lower the level of experience, the higher is the importance given to energy. This finding may indicate that the new generation of practitioners is more focused on energy issues and, in turn, more sensible to environmental concerns than the older generations. As a matter of fact the attention given to the energy issue related to buildings has increased during the last years (Marszal et al., 2011). Indeed scientists and professionals from a variety of fields have been working on this problem for only no more than two decades (Dounis and Caraiscos, 2009).

Domains	Variables	Facility Manager's Rating
Economic performance (X)	Cost performance during planning and design (x_1)	4
	Cost performance during construction (x_2)	5
	Cost performance during operation and maintenance (x_3)	3
	Cost performance during sustainability (x_4)	4
Energy performance (Y)	Performance of heating system (y_1)	3
	Performance of cooling system (y_2)	3
	Performance of lightning system (y_3)	4
	Performance of water system (y_4)	5
Occupant comfort performance (Z)	Performance related to temperature (z_1)	3
	Performance related to humidity (z_2)	4
	Performance related to air quality (z_3)	4
	Performance related to acoustic comfort (z_4)	3
	Performance related to functionality (z_5)	2
	Performance related to psychological aspects (z_6)	5
	Performance related to security (z_7)	3
	Performance related fire protection (z_8)	2

Table 4. Results of Kruskal-Wallis test for years of experience

Smartness Index

The growing awareness of energy-related issues encourages researchers and professionals to strive towards a higher degree of smartness in buildings (Khalil et al., 2011). The Smartness Index (SI) in Equation 1 was developed to capture the level of smartness of a building. For each domain and variable, the mean value of the importance has been computed based on the answers to the survey. Then the weights were obtained through normalization in Equation 2.

$$W_i = \frac{\sum_{j=1}^{j=n} x_{ij}}{n} \qquad (2)$$

where *n* is the number of respondents for variable *i*. The weights (W) so computed are presented in the last column of Table 2. Therefore the Smartness Index (SI) can be calculated as seen in Equations 3 to 6.

$$\begin{aligned} SI &= (W_X \times X) + (W_Y \times Y) + (W_Z \times Z) \\ &= 0.33X + 0.35Y + 0.32Z \qquad (3) \end{aligned}$$

where:

$$X = (W_{X1} \times X_1) + (W_{X2} \times X_2) + (W_{X3} \times X_3)$$
$$= 0.28X_1 + 0.22X_2 + 0.26X_3 + 0.24X_4 \quad (4)$$

$$Y = (W_{Y1} \times Y_1) + (W_{Y2} \times Y_2) + (W_{Y3} \times Y_3) + (W_{Y4} \times Y_4)$$
$$= 0.26Y_1 + 0.27Y_2 + 0.25Y_3 + 0.22Y_4 \quad (5)$$

$$Z = (W_{Z1} \times Z_1) + (W_{Z2} \times Z_2) + (W_{Z3} \times Z_3) + (W_{Z4} \times Z_4) + (W_{Z5} \times Z_5) + (W_{Z6} \times Z_6) + (W_{Z7} \times Z_7) + (W_{Z8} \times Z_8)$$
$$= 0.14Z_1 + 0.12Z_2 + 0.14Z_3 + 0.12Z_4 + 0.13Z_5 + 0.11Z_6 + 0.11Z_7 + 0.13Z_8 \quad (6)$$

The weights of the proposed index can be considered to be reliable since they are based on the opinions of a sample of experts who represent small/medium/large companies, have extensive experience (20-35 years in the industry), and are involved in construction projects as designers/constructors/owners.

According to Carmines and Zeller (1991), content validity is based on the extent to which a measurement instrument reflects the intended domain. It seeks correlation between a theoretical concept and a specific measuring instrument. An extensive literature review was conducted to ensure content validity. The variables representing the issues involved in green building projects were extracted from the works of distinguished scholars publishing in reputable journals.

The index can be easily used by facility managers for the evaluation of the level of smartness of their building and for benchmarking purposes. A facility manager can assess the building's performance in all the variables (X_1, X_2, X_3, X_4,; Y_1, Y_2, Y_3, Y_4; Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8) on a Likert scale of 1-5 and plug them into Equation 1 to determine the level of smartness of their building.

The index could be also beneficial to facility managers since facility managers strive for high performance and high value buildings (Khalil et al., 2011). The ratings of a fictitious facility manager are presented in Table 5 about the evaluation of the smartness of a building.

Table 5. Example Performance Ratings by a Facility Manager

Based on the performance ratings in Table 5, the smartness index can be obtained by using the relationship in Equation 1:

$X = 0.28X_1 + 0.22X_2 + 0.26X_3 + 0.24X_4$

$= (0.28 \times 4) + (0.22 \times 5) + (0.26 \times 3) + (0.24 \times 4)$

$= 3.96$

$Y = 0.26Y_1 + 0.27Y_2 + 0.25Y_3 + 0.22Y_4$

$= (0.26 \times 3) + (0.27 \times 3) + (0.25 \times 4) + (0.22 \times 5)$

$= 3.69$

$Z = 0.14Z_1 + 0.12Z_2 + 0.14Z_3 + 0.12Z_4 + 0.13Z_5 + 0.11Z_6 + 0.11Z_7 + 0.13Z_8$

$= (0.14\times3) + (0.12\times4) + (0.14\times4) + (0.12\times3) + (0.13\times2) + (0.11\times5) + (0.11\times3) + (0.13\times2)$

$= 2.96$

$SI = 0.33X + 0.35Y + 0.32Z$

$= (0.33 \times 3.96) + (0.35 \times 3.96) + (0.32 \times 2.96)$

$= 3.65$

Since facility managers rate the different variables on a 1-5 Likert scale, the Smartness Index SI takes a value between of 1-5, where 1 indicates no smart properties relative to economic, energy and occupant comfort issues, and 5 represents maximum smart properties. The closer the SI of a building to 5, the smarter it is considered to be. If smartness is an important objective, construction owners, designers and constructors should strive for an SI that is as close to 5 as possible.

CONCLUSIONS

This work represents an attempt to structure the main key elements characterizing the notion of smart building that are then integrated and elaborated through a survey. The objectives are twofold: (1) to capture the perceptions of professionals about economic, energy, and occupant comfort issues in smart buildings, and (2) to develop a Smartness Index (SI) that captures the level of smartness in a building.

The first objective has been achieved by administering a questionnaire survey aimed at exploring the perceptions of professionals about smart buildings to the members of CMAA. Responses have been analyzed through the Kruskal-Wallis test that has been used to see the differences between control groups relative to respondents' industry experience and their role in the project team. The results suggest that designers and owners are more focused on energy issues than constructors. This finding may be explained by the fact that the contractor joins the project team typically after the owner and designer have made the decisions related to these issues. Actually, the contractor's input into energy-related decisions can be valuable. The American Institute of Architects recognizes this fact and encourages owners to use an integrated project delivery (IPD) system where, among other issues, the contractor is engaged since the very beginning of the design process, hence contributing not only to energy-related decisions, but also to minimizing constructability problems (AIA California Council, 2007).

Results also show that professionals with fewer years of experience pay more attention to energy-related issues. This finding confirms that acknowledging energy issues is rather a recent event. The greatest push for energy conservation came in the last two decades from the sustainability movement (LEED, 2009). The design and construction of green buildings in the last couple of decades encouraged universities to include these subjects in their curricula, hence sensitizing younger architects and engineers to energy issues. In the long term, it is expected that energy conservation will remain a major design and construction criterion because energy consumption is a very important part of the sustainability equation. From a practical point of view, the energy issue needs to be associated with other aspects that can actually enhance the smartness of a building. This field of research is also acquiring more importance considering that the requirements of thermal and visual comfort, the indoor air quality and the energy efficiency are nowadays extremely significant (Doukas et al., 2009), and smartness represents a challenge for the future development of new buildings, in particular in the light of pollution concerns, energy prices, and more demanding comfort standards. Smart buildings can promote ecological, economical and even cultural sustainability thanks to the adoption of energy conservation techniques, the use of high-efficiency building materials, components, and systems, and the recognition of the daily life inside the building (Kua and Lee, 2002).

The measurement of the smartness of a building is complicated, given that there are many issues that need to be taken into account and that perceptions do differ based on the role of the project participant. The second objective of this study has been achieved by developing a Smartness Index (SI) for buildings that makes use of facility manager ratings and weights calculated by using the responses to a survey. This index can be easily used as evidenced by the example that has been presented in the preceding section. It could be useful for the evaluation of a building's smartness as well as a benchmarking tool against other buildings.

This study is a marked departure from the current building certification models such as LEED and BREAM that assess overall building performance. The contribution of this study is that it pushes to the forefront the "smartness" of a building as a standalone concept that is defined in terms of energy efficiency, life-cycle costs, and user comfort. Information collected through a survey of construction managers provided a better understanding of "smartness" and led to the development of an index that allows benchmarking against other parties in the industry, and competitive actions to produce smarter buildings. The index is simple to use and can be adopted by all parties in a building project easily, hence increasing sensitivity to smarter solutions in building design and construction.

The study is limited by the number of respondents, especially the number of owners. It should also be noted that the results are limited to the construction industry in the U.S. Research is under way to explore professional perspectives and practices in other countries, particularly in Europe and to investigate how practitioners see the future in this field.

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