Li, Mei & Yang, Jay
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Analysis of Interrelationships between Critical Waste Factors in Office Building Retrofit Projects using Interpretive Structural Modelling

Abstract

The number of office building retrofit projects is increasing. These projects are characterised by processes which have a close relationship with waste generation and therefore demand a high level of waste management. In a preliminary study reported separately, we identified seven critical factors of on-site waste generation in office building retrofit projects. Through semi-structured interviews and Interpretive Structural Modelling, this research further investigated the interrelationships among these critical waste factors, to identify each factor's level of influence on waste generation and propose effective solutions for waste minimization. "Organizational commitment" was identified as the fundamental issue for waste generation in the ISM system. Factors related to plan, design and construction processes were found to be located in the middle levels of the ISM model but still had significant impacts on the system as a whole. Based on the interview findings and ISM analysis results, some practical solutions were proposed for waste minimization in building retrofit projects: (1) reusable and adaptable fit-out design; (2) a system for as-built drawings and building information; (3) integrated planning for retrofitting work process and waste management; and (4) waste benchmarking development for retrofit projects. This research will provide a better understanding of waste issues associated with building retrofit projects and facilitate enhanced waste minimization.

Keywords

Interrelationship; waste factors; waste management; office building retrofit; ISM

INTRODUCTION

Office buildings are often associated with high energy consumption and strong environmental impacts. This situation will deteriorate with physical and functional obsolescence of the building stock (Scrase, 2001, Wilkinson and Reed, 2006). Established buildings easily dominate the overall building stock therefore require regular retrofitting to improve their sustainability outcomes (Bullen, 2007).

Australian office markets are relatively mature and characterized by a high need for retrofitting existing aging properties. In 2005, the average age of office buildings since construction or last refurbishment in Australian major capital cities is 17 years for Melbourne, 19 years for Sydney and 13 years for Brisbane respectively (Jones Lang LaSalle, 2005). The duration of a retrofit cycle is estimated to be 25-30 years (Rey, 2004). It indicates that a large proportion of office buildings in Australia need to be retrofitted now or in the next five years. This will help building owners to upgrade their assets, reduce vacancy rates and improve rental income.

A retrofit project usually involves large scale changes in both the internal and external appearance of the building (Holm, 2000), which can lead to intensified waste generation. But waste issues are poorly understood and addressed in office building retrofit projects. Waste is generated in the demolition and installation of interior building elements and settings such as partitions, finishes, fixtures, fittings, furniture and equipment (Baccarini and Bateup, 2008).

The design and construction of office fit-outs is in most cases approached with the short term in mind, in order to meet the rotating needs of new tenants. It often uses high waste quotient materials which are replaced after only a short time (Forsythe, 2010). As the requirement for formal approvals of retrofit projects in Australia depends on the scale or work, waste from these projects is not generally monitored by authorities with the same rigour as is required for new construction.

Waste handling and management can be challenging in office building retrofit projects because of these unique characteristics. Compared to demolition and new build, retrofit work is more risky and complex, less predictable, and often poorly planned (Sanvido, 1991, Egbu, 1994, Rahmat, 1997, McLennan et al., 1998, Reyers and Mansfield, 2001). It is difficult to control even with thorough planning as latent conditions of the existing building may not be discovered until after the work begins (Egbu et al., 1998). This may cause unexpected project variations during work delivery, resulting in increased waste generation. There are often also physical site constraints because of the CBD locations which affect waste sorting and handling (Douglas, 2006). Office retrofits are see simultaneous occupancy of working employees and businesses in a confined space with construction activity, calling for a higher level of coordination of work sequence, time and space utilization (Glardon et al., 1995, Juan, 2009). This limits the capability of site workers to appropriately handle and manage waste on site. Building retrofit work is highly labour intensive, often involving a large number of different subcontractors and trades (Quah, 1992, Holm, 2000, Dulung and Pheng, 2005). It is difficult to standardize waste management practices and subcontractors may not have a high level of organizational commitment to waste minimization. In addition to traditional waste management strategies such as the widely recognized Waste Management Plan, which assists with managing waste already generated, it is necessary to look carefully at waste generation processes, with specific consideration of the characteristics of a retrofit project, in order to support dynamic waste management solutions that integrate effectively with work delivery processes.

In a preliminary study, the authors examined waste variables in general building construction projects through a literature study and compared these to the specific characteristics of retrofit/refurbishment projects (Yang et al., 2011, Li and Yang, 2012). Industry practitioners actively engaged in building retrofit projects were asked to complete a questionnaire survey to establish each variable's probability of occurrence and level of influence on waste generation. Data collected from the questionnaire survey was statistically analysed by using SPSS software. The analysis revealed seven critical factors of on-site waste generation in office building retrofit projects, with each factor comprising several variables. These factors cover a complete range of project situations that lead to waste generation, including organizational issues, project conditions, project delivery and material management. While details of this study are reported separately, results from the preliminary study are shown in Table 1.

{insert Table 1 here}

Based on the findings, this paper presents further research exploring the interrelationships between the critical waste factors, in order to better understand each factor's level of influence on waste generation and propose effective solutions for waste minimization. The paper firstly reviews existing literature on waste generation and management in general construction projects, as well as that specific to building retrofit projects. It then introduces the methods of data collection and analysis in this research, including semi-structured interviews and Interpretive Structural Modelling (ISM), which leads to the establishment of the critical waste factors’ interrelationship model. The key findings from the ISM model and analysis are then discussed, followed by some suggestions proposed for waste minimization in building retrofit projects.

LITERATURE REVIEW

Project level construction and demolition waste management

A review of existing research on project level construction and demolition waste management has revealed a focus on waste minimization, planning, handling, and identification and evaluation of waste management strategy.

The studies tend to focus on technological applications in waste estimation, planning and reduction. For example, Li et al. (2005) explored the application of integrated GPS and GIS technology to the reduction of construction waste. The GIS-based dynamic construction site material layout evaluation model was developed by Su et al. (2012) to improve material accessibility and minimize waste. Zhang et al. (2012) examined the implementation level and barriers of low waste technologies for design and construction. Building information modelling (BIM) based lean production management systems are proposed to improve construction work flows and reduce waste (Sacks et al., 2010). A BIM based system was also developed by Cheng and Ma (2013) for waste estimation and planning.

The simulation and modelling of waste handling and project work processes has become a focus in waste management research, e.g., modelling of the flow patterns of construction processes and waste management systems (Gavilan and Bernold, 1994); waste management mapping models with the ability of cost effectiveness assessment (Shen et al., 2004, Ming et al., 2006); a measurement model for waste management performance (Cha et al., 2009); and an activity based waste generation model for waste prediction (Wimalasena et al., 2010).

Previous researchers have also studied the decision-making processes of best practice waste management strategies and evaluation of their effects. A web-based decision support system for optimal construction and demolition waste management was developed with consideration of both economic and environmental criteria (Banias et al., 2011). Research efforts have also concentrated on the assessment of effects of waste management strategies, in terms of waste minimization (Yuan et al., 2012, Villoria Saez et al., 2013), social performance (Yuan, 2012), environmental impact (Coelho and de Brito, 2012, Ye et al., 2012), and overall effectiveness (Yuan, 2013).

Despite the topic of construction and demolition waste management being widely investigated, very little research has been conducted to address waste problems in a particular type of project, through consideration of the impacts of specific project characteristics on waste generation and management. The physical site constraints and uncertain work nature of building retrofit projects will greatly influence the work flows of retrofitting process and waste management activities accordingly.

Reasons for waste generation in construction projects

Existing research shows that waste generation in construction projects is closely related to inappropriate or inefficient work delivery and material handling processes. Some examples are poor planning and scheduling, inappropriate construction methods, slowness in making decisions, delays to schedules, lack of supervision, repairs on commpleted works, delay of material delivery to site, and damage and loss of materials during transportation and storage

(Alwi et al., 2002, Poon et al., 2004a).

The above mentioned issues that arise during work processes on construction projects are believed to result from poor craftsmanship and on-site labour work. For example, Rafael and Leonhard (1994) identified the main cause of on-site waste to be craftsmen's error, which mainly resulted from poor communication either between crew members or between the contractor and craftsmen. As discovered by Tam et al.(2007), different subcontracting arrangements can cause different levels of material wastage. This can be caused by problems with construction activities, such as delays in on-site operations and low overall efficiency. Higher levels of waste can be generated from work processes requiring a higher level of labour skill (Poon et al., 2004a). Improper work preparation, misuse of equipment and incorrect processing are all believed to be the major causes of waste (Poon et al., 2004b).

In addition to on-site activities, construction waste generation has also been found to relate to design activities (Bossink and Brouwers, 1996). It is estimated that failure to implement waste minimization measures during the design stage of a project leads to 33% of on-site construction waste (Osmani et al., 2008). Design changes occurring at the construction stage were found to be a critical reason for construction waste production (Faniran and Caban, 1998). They may relate to the lack of experience of designers, poor communication and coordination between design and construction teams and increased design complexity (Ekanayake and Ofori, 2000)

Although past research has investigated the links between waste production and design and construction processes, leading to the identification of variables likely to cause waste generation, there has been no exploration of the interrelationships among these variables or their level of influence on waste generation. As retrofit projects present more intense constraints than demolition and new builds (Sanvido, 1991), the reasons for waste generation are more complicated than general building construction projects. This relates to not only the variables leading to the generation of waste but also the interrelationships between them. The level of influence of each of these factors on waste issues needs to be identified, in order to provide better guidance for project stakeholders to plan for, minimize and monitor waste problems in building retrofit projects.

Waste management in building retrofit projects

The few previous studies on waste management in building retrofit projects have focused on waste recovery rates or the level of recycling for building materials and components (Hardie et al., 2006). It has been argued that sound waste recovery practices in building retrofit projects involve consideration of issues such as establishment of markets for dismantled materials and clear responsibility for waste handling (Newton et al., 2009). This previous research echoes common industry practice for building retrofit projects. However, they only address the problems of managing waste that has already produced, rather than addressing its source and the generation process. It also fails to provide any practical guidance for project stakeholders in better understanding waste generation processes in retrofit projects so that appropriate action can be taken.

Effective waste management will not only result in higher waste recovery rates but will also facilitate better project implementation (Jing et al., 2005). Effective waste management will depend on the identification of dynamic waste generation scenarios and planning to coordinate waste management activities and project works. Building retrofit projects usually generate large amounts of waste in the dismantling stage but lack sufficient space for waste handling and processing. Also, unforeseen issues can occur during project delivery, which can lead to unexpected waste generation on site. It is necessary to proactively plan for and control the issues causing its generation to effectively manage waste in building retrofit projects.

Based on the preliminary study which identified the critical factors of waste generation in building retrofit projects, the remaining sections of this paper will explore the interrelationship between the identified factors and propose solutions to address waste problems accordingly.

RESEARCH METHOD

The purpose of this research was to investigate interrelationships between the critical factors of waste generation in building retrofit projects, and identify the characteristics of each factor and its level of influence on waste generation, to assist with waste planning and management. Interpretive Structural Modelling (ISM) was applied as the main approach to fulfil the objective of the research.

ISM provides a means by which researchers can impose an order, build relationships between and create models around the elements of a system (Ahuja et al., 2009a). The method is “interpretive” in that the researcher’s judgment decides whether and how items are related; and “structural” in that creates an overall structure of the relationships between a complex set of items. on the basis of the relationships and “modelling” in that the specific relationships and overall structure are portrayed in graphic form (Warfield, 1974, Sage, 1977, Moore, 1994, Ravi and Shankar, 2005, Ahuja et al., 2009b).

ISM has been used in the study of management issues in different industries, to discovering relationships among the various variables which contribute to a whole system (Hawthorne and Sage, 1975, Watson, 1978, Saxena and Sushil, 1992, Mandal and Deshmukh, 1994, Singh et al., 2003, Bolanos and Nenclares, 2005, Ravi and Shankar, 2005, Rajesh et al., 2007, Ahuja et al., 2009a, Bhattacharya and Momaya, 2009, Ahuja et al., 2010, Pfohl et al., 2011). Although ISM has also previously been utilisedin construction management research, only a few examples can be found, such as technology deployment assessment (Watson, 1978), assessment of the importance of perceived benefits (Ahuja et al., 2009a, Ahuja et al., 2010) and relationship among enablers for construction company growth (Bhattacharya and Momaya, 2009). In addition, ISM has been applied to waste management research scope including evaluation of municipal solid waste management problems (Liao and Chiu, 2011) and the analysis of barriers to development in landfill communities (Chandramowli et al., 2011). An overview of the existing research which utilises ISM techniques confirms that ISM analyses and models can help decision makers visualize issues through a systems approach and then identify factors which have high level of influence and therefore require high prioritisation and substantial effort to resolve. ISM therefore was adopted in this research.

The first step of the ISM approach is to identify relationships between target issues based on consensus of expert views. In this research, semi-structured interviews were conducted to collect opinions of construction practitioners on the interrelationships between the critical factors of waste generation. The interrelationships were not only stated but also explained in detail by the interviewees, in terms of reasons for their opinion and possible solutions to any issues. Semi-structured interviews are well suited for the exploration of the perceptions and opinions of respondents regarding complex issues and enable probing for more information and clarification of answers (Barriball and While, 1994). A “leads to” type approach was chosen to specify contextual relationships between the factors, which identifies that the occurrence of one factor will generally lead to the occurrence of another.

There have only been rare discussions in existing research regarding the number of experts and how to decide on the ideal size of an expert group involved in ISM processes. To ensure consistency of the information, the interviewees of this study were selected from the preliminary questionnaire respondents who also agreed to participate in the interviews. The questionnaire survey sample was established from databases of two prominent industry associations: Master Builders Australia and Green Building Council of Australia. These interviewees are based in companies with building retrofit projects in major capital cities of Australia with developed commercial markets, including Sydney, Melbourne and Brisbane. 15 industry practitioners participated in the semi-structured interviews and of these, approximately 34% were from Government Departments and organisations, 26% from large contractors and 40% representing small and medium subcontractors. Over 70% of are project managers, architects and general managers. Both face-to-face and telephone interviewees were used. The interviewees' profile is shown in Table 2 and Figure 1.

{insert Table 2 here}

{insert Figure 1 here}

The ISM application process and findings following the semi-structured interviews and ISM analysis are discussed and presented in the next section.

ISM ANALYSIS AND RESULT

Structural Self-Interactive Matrix (SSIM)

Based on interrelationships between the factors, which were identified in the semi-structured interviews, the next step of the ISM process was to define these into a structural self-interactive matrix (SSIM). Four symbols are used to denote the direction of the relationship between two factors:

V: Factor i will lead to Factor j ;
A: Factor i will be achieved by Factor j ;
X: Factor i and Factor j will help achieve each other;
O: Factor i and Factor j are not related.

The structural self-interactive matrix with relationships between each pair of factors is shown in Table 3. Detailed information of the factors refers to Table 1.

{insert Table 3 here}

Reachability Matrix

SSIM was then transformed into a binary matrix called the initial reachability matrix by transforming the relationships denoted by V, A, X, O to 1 and 0. The rules for the transformation are as follows:

If (i, j) in SSIM is V, (i, j) in the reachability matrix is 1 and (j, i) is denoted as 0;

If (i, j) in SSIM is A, (i, j) in the reachability matrix is 0 and (j, i) is denoted as 1;

If (i, j) in SSIM is X, both (i, j) and (j, i) in the reachability matrix are denoted as 1;

If (i, j) in SSIM is O, both (i, j) and (j, i) in the reachability matrix are denoted as 0.

Table 4 shows the initial reachability matrix.

{insert Table 4 here}

The transitivity of the matrix was verified and the finial reachability matrix was established. The transitivity of the relationships is a basic assumption made in ISM. It states that if A is related to B and B is related to C, then A is necessarily related to C (Rajesh et al., 2007, Ahuja et al., 2009a). The final reachability matrix in this research is shown in Table 5. The driving power and dependence of each factor are also shown in the table. The driving power is the likelihood of the factor resulting in another factor. The dependence is the extent to which the factor relies on another.

{insert Table 5 here}

Level Partitions

Based on the final reachability matrix, both the reachability set and antecedent set of each factor can be identified. The reachability set for each factor consists of the factor itself and the factors it drives. The antecedent set comprises of the factor itself and the factors which it depends on (Warfield, 1974). The factors with the same reachability set and intersection set are located at the top level of the ISM hierarchy. After each iteration of the model, the factors with no identified level are discarded from the remaining factors (Ravi and Shankar, 2005). After 4 iterations based on the Final Reachability Matrix, as shown from Table 6 to Table 9, four levels were identified in the ISM hierarchy as shown in Table 10. The identified levels of the factors helped establish the ISM model.

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ISM Based Model

Based on the level partitions of the factors and the Final Reachability Matrix, the final ISM based model was established, as shown in Figure 2. This model reflects the interrelationships between the critical waste factors in office building retrofit projects. The single ended arrow indicates that one factor can lead to another factor, while the double ended arrow means the two factors will influence each other.

{insert Figure 2 here}

In the model, “low level of organizational commitment” is located in the first level. It is the essential factor that leads to all other problems. A Project stakeholders’ commitment to waste minimization and sustainability is the most critical factor in achieving effective waste management in office building retrofit projects. Client, consultants, contractors and suppliers need to collaborate and make a joint effort to minimize and manage on-site waste generation. Above this factor is “Lack of plan and design information” which is related to project design stage. The design stage is important for reducing possible errors and variations during project delivery. The quality of documentation developed at the design stage will affect the amount and quality of project information available to project participants, which will impact on waste reduction during the construction stage. At a higher level, there are factors relating to project delivery processes such as “high project complexity”, “more problems in on-site operational management” and “more project variation”. “More material residual and packaging” is the factor located at the top level of the system, indicating that it is influenced by all other issues reflected in the model.

Matrice d'Impacts Croisés Multiplication Appliquée Analysis

Comparing the hierarchy of elements of the ISM model, in the various classifications, results in a rich source of information. Matrice d'Impacts Croisés Multiplication Appliquée (MICMAC) is an indirect classification method to critically analyze the scope of each element of ISM system (Pfohl et al., 2011). MICMAC analysis is conducted based on the Final Reachability Matrix. The objective of the MICMAC analysis is to analyze the driving power and dependence of the factors to classify them into four categories; autonomous, dependent, linkage and independent (Mandal and Deshmukh, 1994). The analysis result is shown in Figure 3.

{insert Figure 3 here}

The factors with higher driving power are more of strategic in orientation, while the dependent factors are more performance orientated. As performance can be improved by continuously improving the driving factors, management needs to address these more carefully (Rajesh et al., 2007). For example, “more material residual and packaging” is a dependent factor with weak driving power but strong dependence on other factors. Minimization of on-site material residual and packaging depends on the commitment and practice of all stakeholders at different stages of the project. “Low level of organizational commitment” belongs to the group of independent/driving factors. It has strong driving power but weak dependence. It is a fundamental factor that initiates other problems during project delivery which contribute to on-site waste.

Linkage factors are those that lie in the middle of the model. They have significant impact on the whole system as they have both strong driving power and strong dependence. These factors are unstable because any activity in these factors will affect other factors and vice versa. In this study, most of the waste factors belong to this category. “High project complexity” for example, can stem from the low quality of documentation of plans and designs. It will also lead to problems with on-site construction management. Proactive and effective planning and management of the linkage factors is necessary and important in waste minimization and project progression.

Autonomous factors have weak driving power and weak dependence and are relatively disconnected from the system. There are no factors in this category, indicating that all factors identified contribute to the overall on-site waste generation system.

DISCUSSION

The ISM model and MICMAC classifications have important managerial implications for project stakeholders around waste planning, minimization and management in building retrofit projects. They convert a complex waste generation system into a structured format and allow practitioners to visualize the reasons for waste generation through a systems approach. The ISM analysis results depict the interrelationships between critical waste factors and their influence levels in the system. Although no step-by-step actions to address the waste factors can be identified from the results, they provide practical guidance for developing and implementing strategies to assist with overall waste reduction. Most issues indicated in the ISM model cannot be overcome quickly and therefore need to be addressed with a long term strategy. The ISM analysis is helpful in determining an approach to each issue which considers the impact on other factors.

It can be noted that the factors related to characteristics and delivery processes specific to building retrofit projects are located on the middle levels of the ISM model. Thesefactors are linkage factors, with both strong driving power and dependence in the system. This confirms that the specific features of building retrofit projects have a significant impact on waste generation. Any waste management measures need to specifically consider these issues to ensure the effectiveness of waste minimization and handling. The design and construction of building retrofits need to be planned and organized to consider minimizing influences of the project nature to enhance waste reduction.

All the issues in the ISM system are directly or indirectly affected by organizational commitment of project stakeholders. This not only refers to motivation, knowledge, recognition and resources needed from the internal company but also identification and coordination of different interests and involvement of various project stakeholders in waste management at different stages of the project. In addition to optimized industry standards and work procedures, this will depend on a shift of industry culture to recognize the importance of waste minimization and raise it as a priority.

Based on findings from the interviews and ISM analysis, some practical measures can be suggested for implementation in building retrofit projects to achieve waste minimization.

Reusable and adaptable fitout design

As reflected in the ISM model, plan and design information is a fundamental issue that can cause problems during work processes. Incompleteness, errors or uncertainty in design information will lead to unforeseen project variations and accordingly an increase in waste generation. It will also increase the possibility of discovering latent negative conditions of the building during the construction phase. To avoid increasing the complexity of a retrofit project, the existing office fit-out is usually completely demolished before the new one is constructed in the building. This results in a large amount of waste on site. A new fit-out design strategy of utilising reusable and adaptable materials and design needs to be developed, to encourage the recovery of materials used in old fit-outs and their use in new fit-outs, to minimize waste generation on site. This design strategy should be included as a standard design element to avoid any uncertainty occurring during retrofitting work processes and to reduce the likelihood of unexpected building conditions being discovered during dismantling.

A system for as-built drawings and building document

According to the ISM model, the lack of “as-built” drawings and limited information about the existing building often increase the amount of waste generated in building retrofit projects. Contractors usually rush for the next job at the end of the current project and therefore don’t always pay detailed attention to the accuracy of their “as-built” drawings. Small scale renovation works are also often not well documented. This will result in a system of building documentation with incomplete and missing information, which is will become a possible cause of project variations and waste generation during future retrofitting works. It needs to become a requirement of building standards and government regulations that contractors complete accurate sets of “as-built” drawings. A computer system of building operation and maintenance records should also be developed for stakeholders to easily store and review documents and information related to completed renovation and refurbishment works on the building. This will ensure all stakeholders have a clear understanding of the condition of the building and can plan, in advance, to manage any components and waste materials generated during dismantling.

Integrated planning for retrofitting work process and waste management

In addition to organizational commitment, issues related to the specific characteristics of building retrofitting works and the possible problems that can occur at different project stages are highly relevant according to the ISM model. Issues relating to planning and design seem to have a definite effect on increasing the complexity of retrofitting processes and causing various on-site problems. Detailed planning of project delivery and effective waste generation processes will help achieve waste minimization and increased waste recovery. Unfortunately this is not yet common practice in the building industry. In the process of planning project delivery, various constraints such as lack of information about the existing building, project risk factors and restricted work spaces need to be taken into account. This will allow for planning in advance for appropriate responses, before and during work delivery on site. During the construction stage of the project, waste generation and management are also influenced by the quality of on-site operational management. It either directly affects the quality of work outcomes, or results in site specific problems in office building retrofit projects. A plan for integrated work delivery, waste generation and waste management needs to be requested in tender documents, as a standard requirement, to engage contractors from the outset. Contractors should be involved early in the project so they can have input into the design documentations and work with project consultants to solve complex problems that take place during the delivery of retrofitting work.

Waste benchmark development for retrofit projects

The interview findings also showed that a major reason for difficulties in waste planning and monitoring in retrofit projects is the lack of waste data and benchmarks. In Australia, waste generation from retrofit projects is not monitored by the Government with the same rigour as new builds. Waste management companies are usually engaged to take on-site waste away. Therefore only waste recovery rates are recorded, rather than waste minimization rates. This results in industry practitioners having little motivation to consider specific issues leading to waste generation in building retrofit projects. A long-term program aiming at developing a waste benchmark for retrofit projects should be initiated and operated industry wide in Australia, preferably by Government or industry associations. This would help to establish an industry standard of waste measurement and accepted amount of waste generation. Governments should also establish appropriate incentive measures, offered within the framework of a waste benchmark program, to encourage industry stakeholders to reduce the amount of waste generated, through optimized management procedures and advanced technologies.

CONCLUSION

This paper investigated the interrelationships between the critical waste factors in building retrofit projects. Based on the findings from semi-structured interviews with industry practitioners, this research utilized ISM to examine the factors' interrelationships through a systematic model. It was found that the organizational commitment of project stakeholders is a fundamental factor in the ISM system. It drives all other issues constituting the system; therefore it is the most fundamental problem in waste minimization. The factors related to planning, design and construction processes reflect the specific characteristics of building retrofit projects and are important linkage factors of the ISM system. They have strong driving impacts on other factors and also tend to be influenced by others presented in the ISM model. The interview findings and ISM analysis have helped propose several suggestions to promote waste minimization in building retrofit projects, including reusable and adaptable fi-tout design, a system for "as-built" drawings and building information, integrated planning for retrofitting work processes and waste management, and the development of a waste generation benchmark.

With reference to the interrelationships between the critical waste factors and proposed solutions to reduce waste, industry stakeholders can better understand waste issues associated with building retrofit projects and implement appropriate measures to improve waste management. Future research will involve validation of the proposed solutions in this paper and exploration of practical ways of applying them in real life practice.

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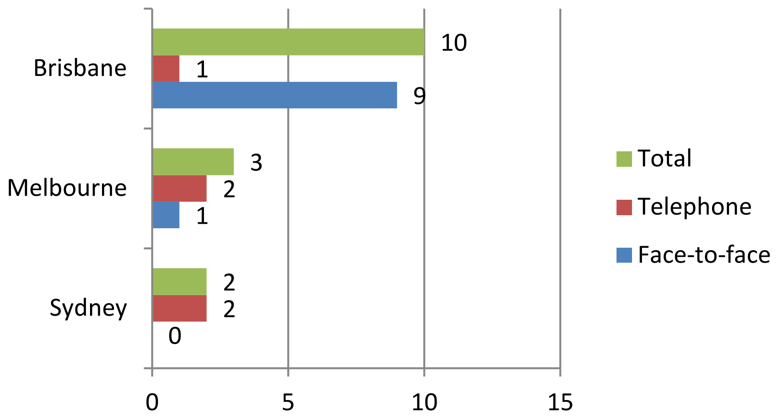

Figure 1. Distribution of Interviewees by Company Location and Way of Interview

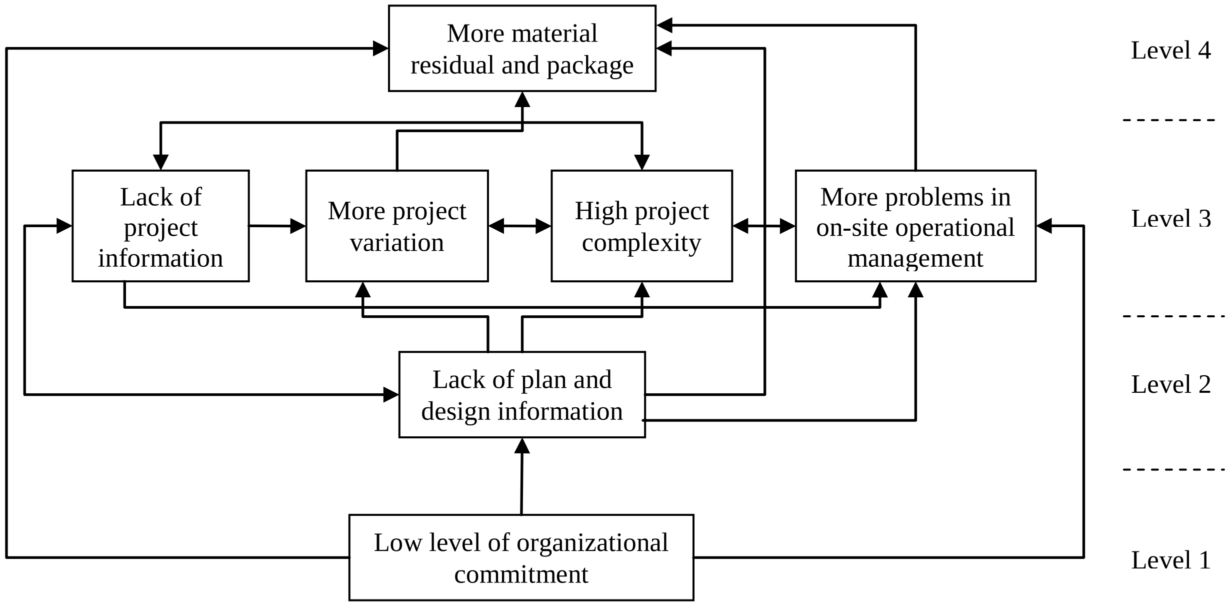

Figure 2. ISM Based Model of Interrelations among Critical Factors of On-site Waste Generation in Office Building Retrofit Projects

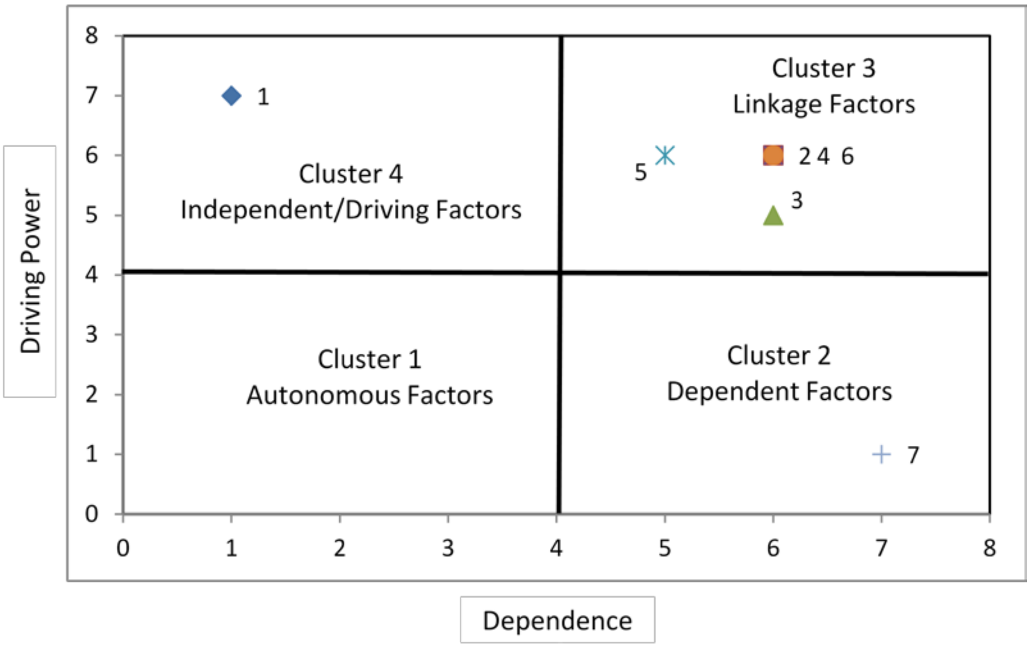

Figure 3. Driving Power and Dependence Diagram

Table 1. Critical Factors of On-site Waste Generation in Office Building Retrofit Projects

Factor	Variable
Factor 1 Project information	F1.1 Lack of as-built drawings
	F1.2 Insufficient information about the existing building
Factor 2 Plan and design information	F2.1 Poor design and specification
	F2.2 Lack of design information
	F2.3 Incomplete or error in contract documents
	F2.4 Delay in making decisions
	F2.5 Cost uncertainty
Factor 3 Project variation	F3.3 Design changes
	F3.4 Last minute client requirement changes
Factor 4 Project complexity	F4.1 Problems discovered during work process
	F4.2 Constrained time schedule for work progress
	F4.3 Physical site constraints
	F4.4 Work undertaken when part of the building remains occupied
	F4.5 Complex process which needs greater coordination
	F4.6 Small packages of work undertaken by subcontractors
Factor 5 On-site operational management	F5.1 Rework of defective items
	F5.2 Lack of coordination and communication
	F5.3 Poor workmanship
	F5.4 Error by tradesperson or labourer
	F5.5 Lack of supervision and control
Factor 6 Organizational commitment	F6.1 Lack of motivation to minimize waste
	F6.2 Lack of knowledge and training of waste minimization
	F6.3 Low level of recognition of importance of waste minimization
	F6.4 Lack of capital, resources and technique for waste monitor and minimization
	F6.5 Not enough collaboration with other contractors orsubcontractors for waste minimization
	F6.6 No company rewards for effective waste management and minimization
Factor 7 Material residual and package	F7.1 Residual from material cutting and package

Table 2. Distribution of Interviewees by Professional Responsibility and Affiliation

Daily job	Affiliation			Total	%
	Large contractor	Small and medium contractor	Government		
Project Manager	2	3		5	33%
Construction Manager	1			1	7%
Senior Sustainability Specialist	1			1	7%
Architect			3	3	20%
Director of Project Services			1	1	7%
General Manager		3		3	20%
Asset Manager			1	1	6%
Total	4	6	5	15	
%	26%	40%	33%		100%

Table 3. Structural Self-Interactive Matrix (SSIM)

Factors	Factor 7	Factor 6	Factor 5	Factor 4	Factor 3	Factor 2
Factor 1	V	V	V	O	O	O
Factor 2	O	V	X	X	V	
Factor 3	V	O	A	X		
Factor 4	O	X	A			
Factor 5	V	V				
Factor 6	V					
Factor 7						

Table 4. Initial Reachability Matrix

Factors	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
Factor 1	1	0	0	0	1	1	1
Factor 2	0	1	1	1	1	1	0
Factor 3	0	0	1	1	0	0	1
Factor 4	0	1	1	1	0	1	0
Factor 5	0	1	1	1	1	1	1
Factor 6	0	0	0	1	0	1	1
Factor 7	0	0	0	0	0	0	1

Table 5. Final Reachability Matrix

Factor	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Driving power
Factor 1	1	1	1	1	1	1	1	7
Factor 2	0	1	1	1	1	1	1	6
Factor 3	0	1	1	1	0	1	1	5
Factor 4	0	1	1	1	1	1	1	6
Factor 5	0	1	1	1	1	1	1	6
Factor 6	0	1	1	1	1	1	1	6
Factor 7	0	0	0	0	0	0	1	1
Dependence	1	6	6	6	5	6	7	

Table 6. Iteration 1 for Level Partitions

Factor	Reachability set	Antecedent set	Intersection set	Level
1	1 2 3 4 5 6 7	1	1	
2	2 3 4 5 6 7	1 2 3 4 5 6	2 3 4 5 6	
3	2 3 4 6 7	1 2 3 4 5 6	2 3 4 6	
4	2 3 4 5 6 7	1 2 3 4 5 6	2 3 4 5 6	
5	2 3 4 5 6 7	1 2 4 5 6	2 4 5 6	
6	2 3 4 5 6 7	1 2 3 4 5 6	2 3 4 5 6	
7	7	1 2 3 4 5 6 7	7	1

Table 7. Iteration 2 for Level Partitions

Factor	Reachability set	Antecedent set	Intersection set	Level
1	1 2 3 4 5 6	1	1	
2	2 3 4 5 6	1 2 3 4 5 6	2 3 4 5 6	2
3	2 3 4 6	1 2 3 4 5 6	2 3 4 6	2
4	2 3 4 5 6	1 2 3 4 5 6	2 3 4 5 6	2
5	2 3 4 5 6	1 2 4 5 6	2 4 5 6	
6	2 3 4 5 6	1 2 3 4 5 6	2 3 4 5 6	2

Table 8. Iteration 3 for Level Partitions

Factor	Reachability set	Antecedent set	Intersection set	Level
1	1 5	1	1	
5	5	1 5	5	3

Table 9. Iteration 4 for Level Partitions

Factor	Reachability set	Antecedent set	Intersection set	Level
1	1	1	1	4

Table 10. Level of Factors

Level	Factor
1	Factor 7 “material residual and package”
2	Factor 2 “project information”
	Factor 3 “project variation”
	Factor 4 “project complexity”
	Factor 6 “on-site operational management”
3	Factor 5 “plan and design information”
4	Factor 1 “organizational commitment”