TOWARDS ACHIEVING SUSTAINABILITY THROUGH CONSTRUCTION WASTE MANAGEMENT BY INTEGRATION OF DESIGN AND BUILDING INFORMATION MANAGEMENT

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ABSTRACT
With the rapid growth in construction activities as a result of growing population and urbanization, increase of construction material prices, lack of material resources, limited funds and environmental issues, construction waste is becoming a serious problem in Egypt and all over the world and still there is a lack of attention to such subject. The research contains a survey highlighting that at the construction stage, 68.81% of work is completed without shop drawings approval, 84.62% of specification changes, 86.54% of problems occur in construction and many other factors, so instead of handling construction waste at construction stage, as most current research has done, construction waste management must be planned at the architectural design stage, looking forward to the future of buildings as sustainable elements and how it will cost us environmentally until the construction is completed. Traditional methodology of architectural building design has been illustrated through a case study of residential building as a result a high amount of wastage, CO_2 emissions, environmental and cost impacts that have occurred. After that, an integration methodology combining architectural design for construction waste management and building information management have been implemented using building information modelling through a case study after redesigning and optimization. As a result of new architectural design methodology implementation there is minimization in CO_2 equivalent produced by 10.43% in glazing panels and 17.42% in porcelain tiles, compared to traditional methodology. The integration between building information management and design for construction waste management at design stage through sustainability approach could prevent and or minimize the environmental impacts in Egypt and many other places. It is hoped that it may provide the Egyptian government, local experts, decision makers and contractors a method to enhance, save country resources and minimize the environmental impacts of construction industry.
Keywords: architectural design, design for construction, sustainable design, building information management, waste management, environmental impacts, CO_2 minimization, building information modelling.

1 INTRODUCTION

The population of Egypt is estimated to be 107,770,524 in 2022. Approximately 95% of the population lives within 20 km of the Nile River and its delta; vast areas of the country remain sparsely populated or uninhabited. Over the last 10 years there is a major change and rapid urban growth. Urban population is 43% of total population in 2022, the rate of urbanization or annual rate of change, 1.9% (2020–2025 estimated) [1].

So, there is a rapid construction activity and new cities are being constructed such as Egypt's new capital, Al Alamin, Al Galala and more new cities.

Over the decades, building construction activities have generated the largest volume of waste across the globe [2]. This waste could be attributed to the constant uptake of construction, demolition and renovation activities during which villages are built into towns, towns into cities and cities into mega cities [3]. In fact, this uptake of building activities results in about 30% of the total annual waste generation worldwide [4]. As shown in Fig. 1,

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the most preferred option in dealing with construction waste is to be prevented and the second option is minimization which is the core aim of the research.

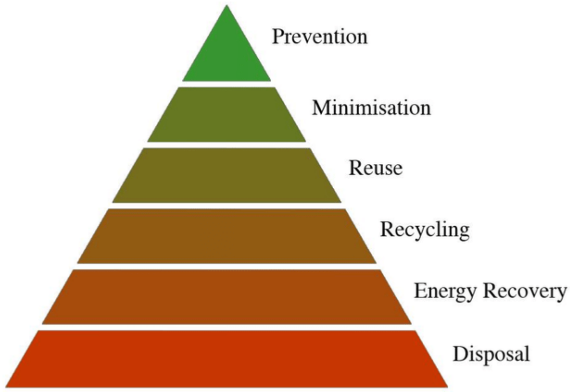

Figure 1: Construction waste management options [5].

1.1 Problem background, aim and objectives

This research is an attempt to study the current situation with regard to construction waste in Egypt and how the integration between building information management and architecture design for construction waste management can enhance the Egyptian construction by preventing and minimizing the construction waste from design stage before construction, in the hope that it may provide the Egyptian government, local experts, decision makers and contractors a method to enhance and save country resources, energy, time, costs, manpower, and minimize the environmental impacts of construction industry. Implementation of traditional architectural design methodology in a case study of residential building using building information modelling (BIM) and analysing the percentage and amount of construction waste; also identifying and converting the amount of material wastage percentage into kg CO_2 equivalent which has been generated in the project case study versus the amount which has been saved by implementation of the new methodology.

1.2 Hypothesis and methodology

By integrating building information management and architectural design for construction waste management in design stage before construction in the Egyptian construction industry can prevent and minimize construction waste in material, time and cost and will help to get growing economy, return on investment and avoid the environmental impacts.

The methodology used to identify, clarify and test new approach is a frame work methodology, with research problem, aims and objectives presented as input No. 1 and integrating literature review and existing related works as input No. 2. The new methodology can then generate a new approach based on the integration between theories as output after passing through an iterative process. As outcomes of the integration process, the research will highlight new quotations. The research is combining qualitative and quantitative research approaches. A comparison with results will be highlighted as validation of the research along with the results.

2 LITERATURE REVIEW

2.1 Building information modelling

This represents the process of development and use of a computer-generated model to simulate the planning, design, construction and operation of a facility. The resulting model, a building information model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility [6].

There are plenty of benefits from using BIM in a project, but the most important aspect of BIM comes during the early design stage where many important decisions are being taken [7].

BIM is the future of construction and long-term facility management but there is still much confusion about what exactly it is and how it should be utilized and implemented [8]. BIM is a relatively new technology in an industry typically slow to adopt change [9]. One of the most important differences of BIM's existing technologies in the design and construction sector is that it has a potential to accommodate all participants and processes [10].

2.2 Causes of construction waste related to architectural design

The main causes of construction waste at the construction stage related to architectural design are lack of information about types and sizes of materials on design documents, design changes and revisions, errors in information about types and sizes of materials on design documents and determination of types and dimensions of materials without considering waste [11]. There are two main causes of construction waste related to design such as change to design and choices of specifications [12].

In Singapore, the sources of construction waste related to design are organized as lack of attention to dimensions, changes made to design while construction is in progress, lack of information in drawings and designer's unfamiliarity with material alternatives [13]. Unclear specifications, not defining material types, lack of and conflicting detailing are from the top mean rank which result to construction waste which need to be avoided [14]. According to Royal Institute of British Architects (RIBA), there are four stages of design which is preparation and briefing, concept design, spatial coordination and technical design [15].

2.3 Building information management and design for construction waste management

Ahankoob et al. [16], Rajendran and Gomez [17] and Lu et al. [18] introduced the potential use of BIM technology to minimize construction waste, but these efforts were limited to the design phase and did not discuss the specific methods to utilize BIM. Furthermore, the UK construction 2025 strategy recognized that BIM has the potential to reduce construction waste during the design and construction stages [19].

3 SURVEY

A survey has been taken by an expert group related to design for construction waste management and 70 responses have been collected. The survey is part of the research. Survey participants are: 35.82% design architects, 22.39% technical architects, 14.93% BIM engineers, 10.45% project and construction mangers and 16.41% consultants, material and planner engineers. 78.75% of the participants are in senior and management level with experience from 5 to more than 10 years. The majority of survey participants have agreed on never having worked on implementation of design for construction waste management through building information management as a design strategy for avoiding and minimizing construction waste.

78.95% of survey participants have highlighted that the project cost after design has been approved by client in design stage, despite that 84.62% of survey participants have stated that the client has requested cost reduction in construction stage for packages such as external glazing, flooring and wall works.

35.29% of survey participants have stated that the design change request in construction stage takes long time in processing compared to project timeline while 27.45% have stated that a design change has been requested and, as a result, there was delay in processing; work has been completed at the construction site then design change request drawings have been approved. 68.81% of survey participants have been highlighted that construction work at site has been completed without approved shop drawings and shop drawings are approved after work completion.

21.15% of survey participants have stated that managing construction waste at design stage would be accurate in avoiding and minimizing construction waste while 46.15% have stated that involving supplier factories would be the most accurate proposal in avoiding design errors and so on construction waste.

In addition to that, 32.69% have stated that it will be accurate at construction stage to involve supplier's factories which is among the main reasons for construction waste increment. Involving supplier's factories at design stage is the best proposal for avoiding design errors at construction stage and for the design to be coordinated and detailed. Specification changes at construction stage is critical action that will result to missing in coordination and design errors. 84.62% of survey participants have stated that one or more items in the project design's specifications have been changed. 71.15% of survey participants have stated that material wastage is being calculated depends on the design which means that there is no specific rule or methodology in calculating material wastage which lead to over ordering and increment in material wastage.

86.54% of survey participants have stated that they have faced problems in construction stage related to design. 98.07% of survey participants have stated that design change orders are affecting project timeline and lead to reworks and so on material wastage; that is why design change orders need to be avoided and at least minimized.

Related to design problems and errors at construction stage related to design: 13.46% of survey participants have stated that reworks were the solution while 34.62% have stated that it required change in the approved design drawings. Moreover 38.46% have stated that the defects in design resolved at construction stage by preparing more construction details while 13.46% have stated that it was required change in design specifications. 92.16% of survey participants have stated that they are preparing construction details at construction stage which takes long time to be coordinated and to be approved and leads to many issues during construction; design as a package need to be coordinated and construction details to be approved before construction.

4 CASE STUDY OF TRADITIONAL METHODOLOGY IN BUILDING DESIGN

A case study of a residential building in Riyadh, Saudi Arabia (Fig. 2), was completed on 14 October 2022 at a site based on the traditional building design methodology. The project case study consists of four floors and a built-up area of 3,120 m^2.

Figure 2: Case study of residential building exterior architectural design actual as built.

4.1 Traditional design methodology in building design

4.1.1 External glazing

After implementation of the manufacturing glazing panels whose dimensions are (3.21 m × (1.92, 2.0, 2.25, 2.55, 3.66, 4.5 5.10, 6.00 m)), 9.01 m^2 of glass panels is required to be wasted; considered as a percentage, 10.43% wastage in glass panels of double glazing have been produced for an elevation sample of 86.47 m^2 with considering optimization of glass manufacturing panels according to traditional architectural design methodology.

In a previous laboratory case study, 1 m^2 of aluminium glazing frame with double glazing glass panels with break produce 1,672 kg CO_2 equivalent [20]; in order to highlight kg CO_2 equivalent for the glass panels only without considering the aluminium frame, the value of 1 m^2 of aluminium framing kg CO_2 equivalent of 486 kg CO_2 will be used [21]. Glass panel kg CO_2 equivalent is 1672 − 486 = 1,186 kg CO_2 equivalent. The following equation has been used in order to calculate the kg CO_2 equivalent.

$$\text{Glass panels material wastage } (m^2) \times \text{material specification kg } CO_2 \text{ equivalent.}$$

By implementation of the above equation, 9.01 m^2 × 1,186 kg CO_2 = 10,685.86 kg CO_2 equivalent have been produced for an area of 92.16 m^2.

4.1.2 Tiles

In the case study, a total area of 159 m^2 were analysed and 28.66 m^2 of tiles waste have been produced and transferred to landfill sites. The environmental impact of kg CO_2 equivalent reference in Mirage tiles which have been used in the case study is 16.96 kg CO_2 per square metre of tiles [22] in compliance with ISO 14025 and EN 15804.

Due to the 18% of waste which have been produced in tiles which considered: 28.66 m^2 × 16.96 kg CO_2 = 486.073 kg CO_2 equivalent. The equation which has been used for calculating the amount of material wastage kg CO_2 equivalent:

$$\text{Material wastage amount } (m^2) \times \text{material specification kg } CO_2 \text{ equivalent}/m^2.$$

5 STAGES AND VALIDATION OF DESIGN FOR CONSTRUCTION WASTE MANAGEMENT (DFCWM) METHODOLOGY IMPLEMENTATION

5.1 External glazing

5.1.1 Design stage (preparation) for external glazing

At that stage, the designer must consider the illustration in Fig. 3 in order to develop the project information. Furthermore, the designer prepares a building information management plan for the architecture design of external glazing illustrated in Table 1.

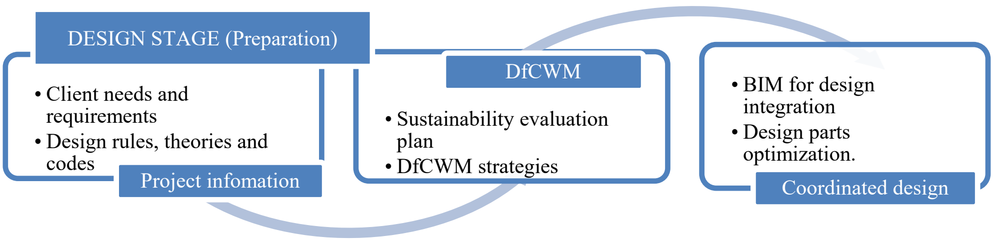

Figure 3: Design stage (preparation) diagram.

Table 1: External glazing sustainability and building information management plan.

Sustainability evaluation plan for external glazing (by researcher)			
Glazing			
Design rules and constraints	To be considered in specifications, colour and other constraints depends on design region and location		
Manufacturing standards	3.21 × (1.92, 2.0, 2.25, 2.55, 3.66, 4.5, 5.10, 6.00) m		
Suggested dim. usage panels	3.21 × 4.5 m	3.21 × 5.10 m	3.21 × 6.00 m
Wastage limits	Not exceed 1%		
Aluminium tubes			
Design rules and constraints	To be considered in specifications, colour and other constraints depends on design region and location		
Manufacturing standards	From 3.00 m to 6.00 m		
Wastage limits	Not exceed 1%		
Building information management plan for external glazing (by researcher)			
Glazing and aluminium tubes			
Tools	Autodesk Revit, Autodesk Navisworks and Microsoft Excel		
Design components in relation	Glazing in relation to plasterboard ceiling and flooring tiles		
Manufacturing standards	Optimization through BIM for each space in coordination		
Glazing	3.21 × (1.92, 2.0, 2.25, 2.55, 3.66, 4.5, 5.10, 6.00) m		
Plasterboard panels	2.40 × 1.20 m		
Tiles (flooring)	0.60 × 0.60 m	0.8 × 0.8	1.20 × 0.20
Tile joints	1.5 mm	1 mm	
Space dimension optimization (SDO)	Through BIM for DfCWM in glazing elevation in coordination with other design components		

5.1.2 Concept design for external glazing

At this stage, the designer has developed the design requirements from project information inputs. The designer has ensured that the design is aligned with sustainability outcomes (Fig. 4, Table 2).

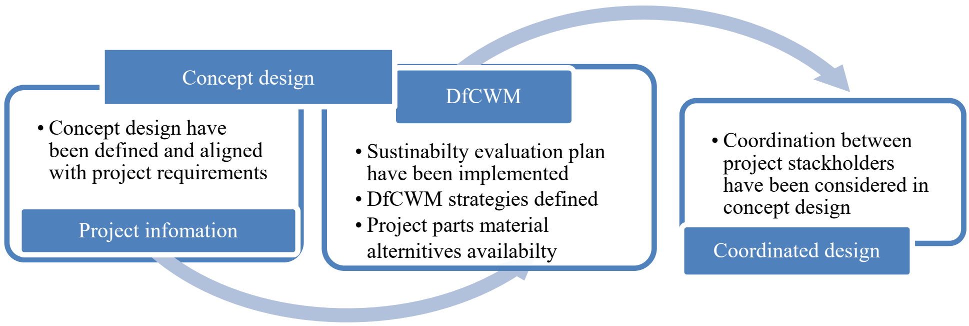

Figure 4: Concept design diagram.

Table 2: Illustration of DfCWM strategies which were used in external glazing.

Design for Construction Waste Management (DfCWM) strategies for external glazing (by researcher)	
Glazing and aluminium tubes	
Tools	Autodesk Revit, Autodesk Navisworks and Microsoft Excel
Strategies	Cut and fill, modularity, simplification and easy to handle (EtH)
Optimization	In spatial coordination stage
Verification	In technical design stage
Staking and handling	In construction stage

5.1.3 Spatial coordination for external glazing

At this stage, the concept design has been developed and the design is taking a further step to more details. The elementary architecture modular system for external glazing has been developed as illustrated in Fig. 5.

In Fig. 6, the architectural design dimensions for the elevation have been optimized as per manufacturing standards of exterior glazing. The gross total height was adjusted from 9.41 to 9.60 m and gross total width adjusted from 9.19 to 9.60 m; the optimization and adjustment has prevented material waste in construction.

5.1.4 Technical design for external glazing

At this ultimate stage of the design, the designer must consider the diagram of Fig. 7 to ensure that the design has met the design for construction waste management methodology.

Verification of construction waste in quantity of external glazing materials must be applied through BIM in order to verify the results in sustainability evaluation plan as illustrated in Table 3.

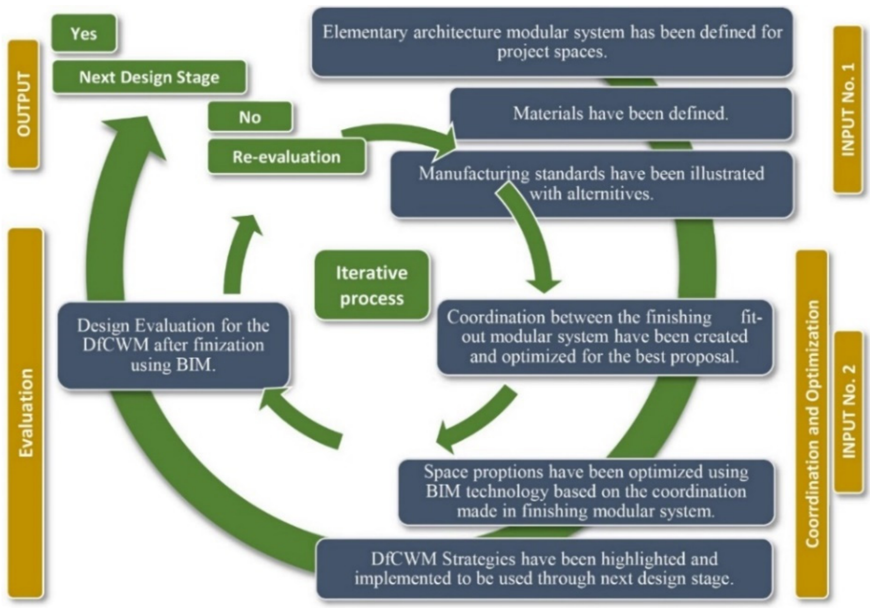

Figure 5: Spatial coordination diagram.

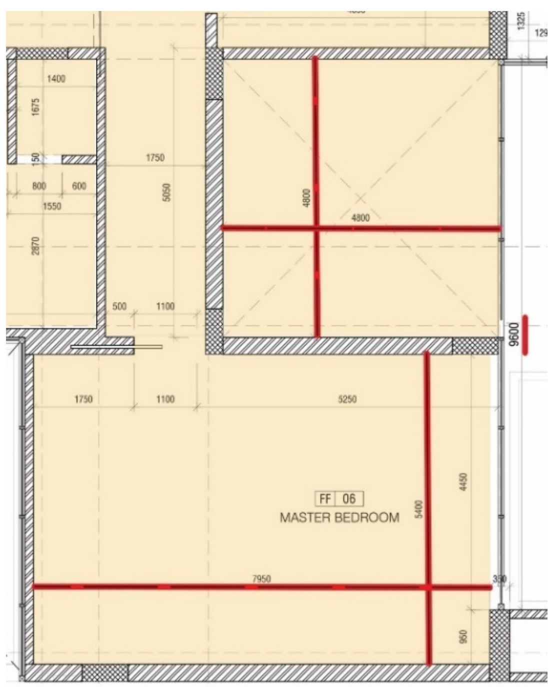

Figure 6: Illustration of modular system of external glazing with DfCWM consideration and coordination with space dimensions.

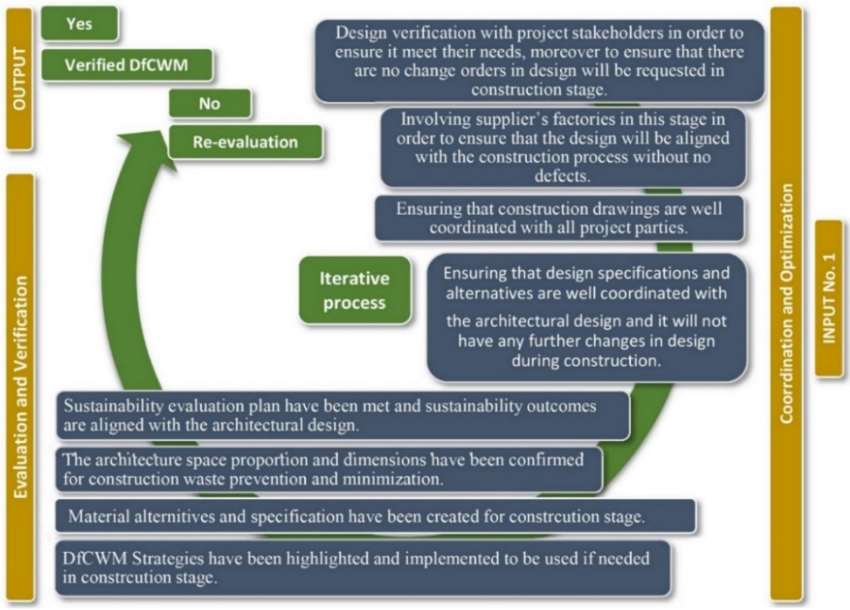

Figure 7: Technical design diagram.

Table 3: External glazing quantity of construction waste verification.

Exterior glazing waste analysis for elevation (by researcher)						
Manufacturing standards of 3.2 × 5.1 and 3.2 × 4.5 m have been used						
Elevation gross dimensions 9.6 × 9.6 m						
List of cutting glazing panels		Wasted cut piece dimensions (m)		Wasted cut piece area (m^2)	No. of pieces wasted	Waste by (m^2)
Length (m)	Width (m)					
5.1	3.2	0	0	0	0	0
Waste by (m^2)						0.00
After analysis cut pieces considered for reuse at construction site cells highlighted (m^2)						0
Net waste will be transferred to landfill						0.00
Total area of figure analysed (m^2)						92.16
Waste percentage						0.00%

The following equation has been used in order to calculate the kg CO_2 equivalent which have been produced after analysis of Fig. 6 glazing:

Glass panels material wastage (m^2) × material specification kg CO_2 equivalent.

In order to highlight the kg CO_2 equivalent for the glass panels only without considering the aluminium frame, the value of 1 m^2 of aluminium framing kg CO_2 equivalent of 486 kg CO_2 will be used [21] while considering the value kg CO_2 equivalent/m^2 of glass panels with break and aluminium framing produce 1,672 kg CO_2 equivalent [20]. So that glass panel only kg CO_2 equivalent is 1672 − 486 = 1,186 kg CO_2 equivalent.

By implementation of the previous highlighted equation for aluminium tubes and glass panels using the references values in Sinha and Kutnar [21] for aluminium framing and in Maria et al. [20] for glazing panels, waste which have been produced after implementation of the methodology is 0 $m^2 \times 486$ kg $CO_2 = 0$ kg CO_2 equivalent have been produced and 0 $m^2 \times 1186$ kg $CO_2 = 0$ kg CO_2 equivalent for area of 92.16 m^2 illustrated in Fig. 6 which means the negative sustainability impacts on the environment have been avoided.

5.2 Tiles

5.2.1 Design stage (preparation) for tiles

At this stage, the designer must consider and develop the project information related to tiles and its alternatives based on the stakeholder needs. Preparing of practical sustainability evaluation plan and constrains for tiles material waste to be considered in further design stages as illustrated in Table 4.

Table 4: Tiles sustainability evaluation and building information management plan.

Sustainability evaluation plan for tiles (by researcher).		
Tiles		
Design rules and constraints	To be considered in specifications, colour and other constraints depends on design region and location	
Manufacturing standards	(0.6 × 0.6) or (0.8 × 0.8) or (1.2 × 0.2) m	
Suggested dim. usage	0.6 × 0.6 m	1.2 × 0.2 m
Wastage limits	Not exceed 1%	

Building information management plan for tiles (by researcher).		
Tools	Autodesk Revit, Autodesk Navisworks and Microsoft Excel	
Design components in relation	Tiles in relation to wall finishing according to design	
Manufacturing standards	Optimization through BIM for each space in coordination	
Tiles	(0.6 × 0.6) or (0.8 × 0.8) or (1.2 × 0.2) m	
Stone	(0.8 × 1.2) m	
Cement plastering and paintings	Around 25 mm	
Wood cladding	25 mm Cement plastering + (12 mm substructure +18 mm cladding) = Total 550 mm	
Marble walls	Optimization in coordination with marble minimum wastage	
Tile joints	1.5 mm	1 mm
Space dimension optimization (SDO)	Through BIM integration with DfCWM for tiles in coordination with other design components	

5.2.2 Concept design for tiles

At this stage, design requirements have been developed from project information, plans have been prepared and the designer has ensured that the design will be aligned with sustainability outcomes. The concept design of tiles has been prepared, specifications and alternatives have been illustrated. The design options for tiles will be optimized and chosen in spatial coordination stage though the optimization with other project parts and space proportions dimensions. Furthermore, the design parts in relation with tiles have been defined for optimization in further design stages through BIM modelling as illustrated in Fig. 8. If possible, it is suggested for tiles to be cut and numbered and transferred to construction site for direct installation in order to avoid any possibility for wastage.

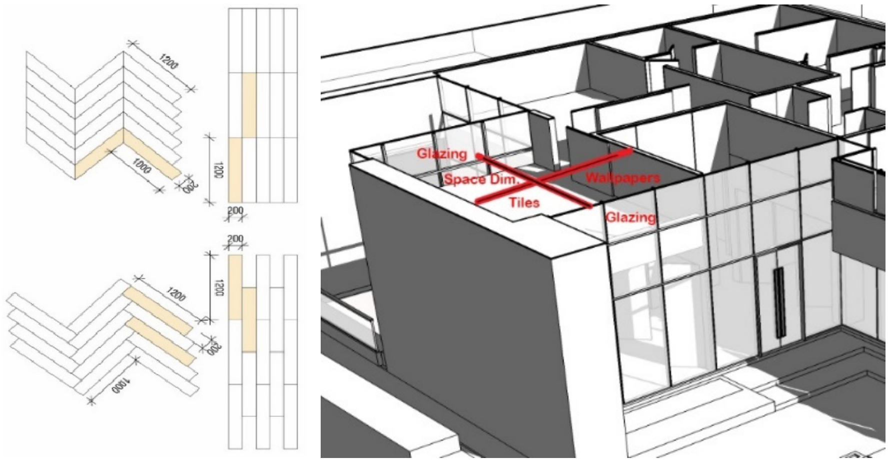

Figure 8: Initial design options for tiles in concept design stage and tiles relation with other design parts in spaces design proportions.

5.2.3 Spatial coordination for tiles

At this stage, the coordination with project parts in spaces is the main focus. After the concept design for each project part has been defined with its alternatives, the optimization and coordination through BIM for construction waste avoidance and minimization will take its place as illustrated in Fig. 5.

The architectural finishing on walls and tile spacers joints must be defined and considered in preparing the tiles layout optimization for avoidance and minimization of waste. In Fig. 9, there are 41 tiles in the tile layout and the spacers has been selected to be 1.5 mm, so a total of 6 cm in space length will be considered while there is 2.5 cm in each side of the walls of the space, so the space will have 41 tiles in length with full dimensions without any wastage.

Not considered dimensions in tile layout design = (Number of tiles in proposed layout − 1) × (tile spacer selected thickness) + (Space length or width total wall finishing dimensions).

Many designers do not detail dimensions such as tile spacers while designing space dimensions which result to many not used cut pieces and so on construction material wastage in construction stage.

5.2.4 Technical design for tiles

At this stage, the tiles design has been chosen and implemented through the previous stage. Table 5 illustrates the percentage of waste after consideration of DfCWM being below 1% which proves the successful implementation of avoidance and minimization of tiles waste. Fig. 10 illustrates the cut and fill strategy implementation through BIM program (Autodesk Revit). Total number of 41 pieces of 0.6 × 0.20 m will be cut and filled and reused in master bedroom lobby resulting to 0.58% of wastage in material of tiles.

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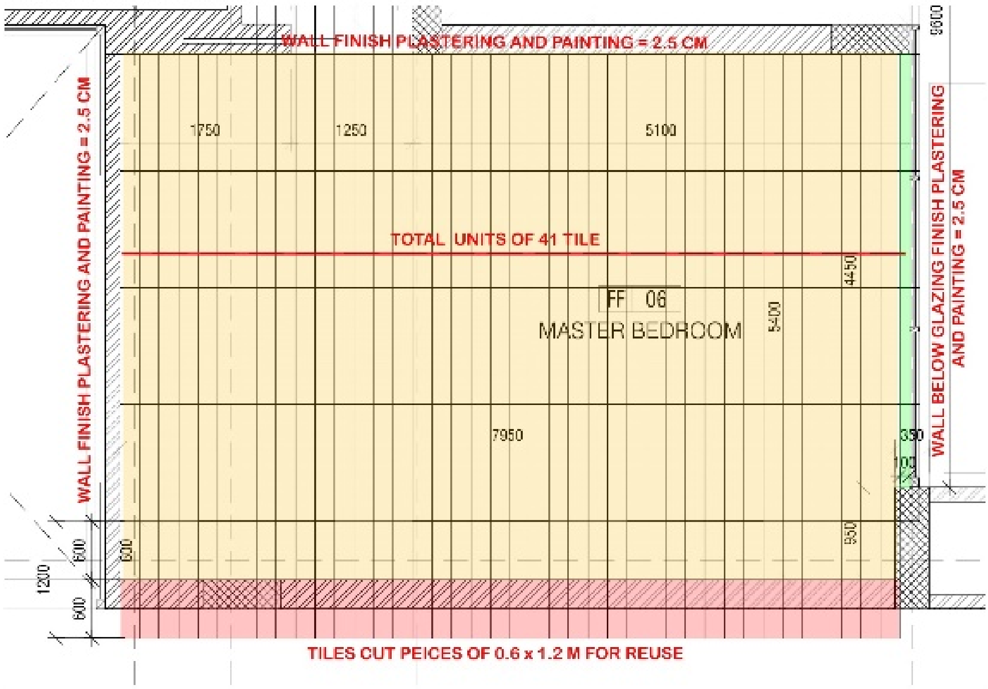

Figure 9: Illustration of tiles consideration of wall finishing using BIM Autodesk Revit.

Table 5: Illustration of DfCWM strategies which used in tiles (by researcher).

Design for Construction Waste Management (DfCWM) strategies for tiles	
Tools	Autodesk Revit, Autodesk Navisworks and Microsoft Excel
Strategies	Cut and fill, modularity, simplification in design and minimization of skilled labourers mistakes
Optimization	In spatial coordination stage
Verification	In Technical design stage
Staking and handling	In construction stage

The environmental impact of kg CO_2 equivalent reference in Mirage tiles which have been used in the case study is 16.96 kg CO_2 per square metre of tiles [22] in compliance with ISO 14025 and EN 15804.

As illustrated in Table 6, area of case study figure of 69 m^2 after design optimization and integration between DfCWM and building information management, 0.58% of tiles waste have been produced and sent to landfill. Due to the 0.58% of tiles waste which have been produced in tiles which considered as 0.40 $m^2 \times$ 16.96 kg CO_2 = 6.784 kg CO_2 equivalent have been produced which has a negative sustainability impact on the environment. The equation which have been used for calculating the amount of material wastage kg CO_2 equivalent is:

$$\text{Material wastage amount } (m^2) \times \text{Material specification kg } CO_2 \text{ equivalent}/m^2.$$

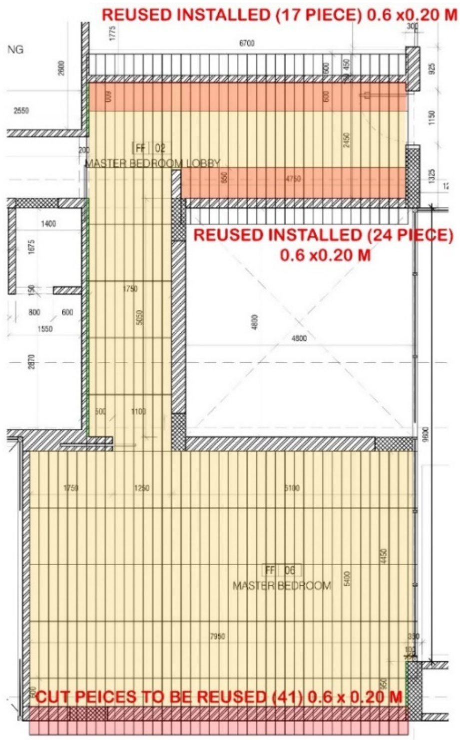

Figure 10: Tiles cut and fill strategy using BIM Autodesk Revit.

Table 6: Tiles quantity of construction waste verification.

Tiles waste analysis for tile area in Fig. 10						
Manufacturing standards 0.20 × 1.20 m have been used – tile spacers of 1.5 mm						
Tile area in Fig. 10 = 69 m^2						
Tiles cutting list				Reused installed	Full piece to be cut 0.6 × 1.2	Waste by (m^2)
Length (m)	Width (m)	No. of tiles	No. reused			
0.6	0.2	41	41			0
0.6	0.2	33	0	33		0
0.6	0.2	24	0	8	16	0
0.8	0.05	1	0	0	0	0.04
1.2	0.05	6	0	0	0	0.36
Waste (m^2)						0.40
After analysis cut pieces considered for reuse at construction site cells highlighted (m^2)						4.92
Net waste will be transferred to landfill (m^2)						0.40
Total area of figure analysed (m^2)						69
Waste percentage						0.58%

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Table 7: Comparison between traditional methodology in building design and design for construction waste management methodology.

Wastage percentage (%) in materials.				
	Methodology		Area analysed	kg CO_2 equivalent saving
Fit-out	Traditional methodology	DfCWM methodology		
External glazing	10.43% in glass panels	0.00% in glass panels	92.16 m^2	10,685.86
Tiles	18%	0.58%	69 m^2	210.93
Design flexibility and errors				
Waste avoidance minimization	Not considered	Considered	The more quantities the more construction waste minimization	
Change orders	Many change orders that affect project timeline and lead to waste in materials and cost overruns	There is no change orders or changes are minor does not affect project timeline or lead to material waste and cost overruns		
Design errors	Many design errors	There is no design errors or errors are minor, alternatives are available		
Design coordination	Not coordinated details wise	Well-coordinated		
Strategies	No specific strategies	Cut and fill, modularity, simplification and design optimization (DO)	Adapted to spaces	
Level of detailing	Minimum level of details	High level of details	Focused space details	
Sustainability and cost impacts				
Material wastage	High	Avoided or minimum		
Energy	Wastage of energy	No wastage		
Landfill	High use of landfill	Landfill not required		
Environmental effects	High	Avoided or minimum		
Inflation	Material prices increment	Lead to stability in material prices		
Project cost	High	Minimized		

6 CONCLUSION

The results indicated that traditional methodology in buildings architectural design does not consider the sustainability dimension which is being affected due to construction waste increment. The study presents and analyses the result of expert survey regarding architectural defects in architectural design in buildings related to construction waste at construction stage.

There are two methodologies discussed in the research namely, traditional design methodology and design for construction waste management methodology. Table 7 illustrates a comparison between the two design methodologies. As a results of new architectural design methodology implementation there are minimization in CO_2 equivalent produced by 10.43% in glazing panels and 17.42% in porcelain tiles, compared to traditional methodology. The integration of the new architectural design methodology using BIM need to be implemented urgently within construction sector. The results of the study will have dramatic sustainability effects that will prevent and minimize the construction industry impacts on the environment and will save world resources. The research is recommended to be implemented with the government, owners, designers, suppliers and contractors.

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