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Efficient Construction Waste Management: A Solution through Industrial Revolution (IR) 4.0 Evaluated by AHP

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Abstract: Construction waste management is a global concern not only because it impacts the financial efficiency of construction projects, but also because of its negative influence on the environment. The construction industry is a major contributor to environmental pollution due to its carbon footprint and greenhouse gas emissions. Thus, effective construction waste management solutions are required for sustainable development by preventing material waste. Hence, this study employed the Analytical Hierarchy Process to prioritize the possible construction waste, factors leading to its generation and the most effective IR 4.0 solution. A questionnaire was constructed, and after refinement, it was then distributed among the engineers, contractors, professors, and other industry professionals. The results from the analysis provide us with the list of factors ranked on their comparative weightage and score. The wastage of cement due to moisture is found to be the highest ranked potential waste. Moreover, changes in orders by the client are termed as the most highly ranked cause of rework and material wastage. Similarly, the Industrial Building Systems are the best solution for efficient construction waste management that Industrial Revolution 4.0 can provide. The results of this study can help to enhance project control by providing information on possible construction wastes and the factors that lead to their generation.

Keywords: construction waste; sustainable construction; natural resources; Industrial Revolution 4.0; Industrial Building Systems (IBS)

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1. Introduction

The world is trying to deal with an ever-increasing waste problem; thriving societies and economies around the world generate an enormous amount of assorted waste every day [1–3]. According to the European Union (EU), vast quantities of waste can no longer be absorbed by nature, and the Earth's resources are finite, rapidly becoming scarce. Mankind now consumes more resources than earth's ecosystem can regenerate in a year; the famous Earth overshoot day is that mark [4]. Consequently, there are detrimental effects on ecosystems and the sustainable environment. Estimates are that construction waste comprises 40% of the world's overall waste, whereas domestic waste is 24%, and the manufacturing industry contributes 21% [5]. The construction industry alone is responsible for 40% of global greenhouse emissions compared to the aviation industry, which has only a 2–3% carbon footprint. It is pertinent to mention here that the cement industry alone is generating a quarter of the total industrial CO_2 emissions and accounts for 5–6% of overall CO_2 generated by human activities [6].

However, the construction industry is an essential segment of a country's economy and is essential for providing public and private infrastructure [7,8]. Furthermore, it provides 5–10% of the population with employment opportunities [9] and accounts for 10% of the country's economic growth as well [10]. Since the construction sector consumes a considerable number of natural resources, resulting in a substantial amount of waste, the construction industry is not completely sustainable and has its effects on the environment. The resource consumption and waste generation ratio are unsustainable because of the "use and through" philosophy [11]. Still, even the world's biggest economies cannot provide a high standard of living without undertaking continuous infrastructure projects, and because it contributes more to GDP than its detrimental effects [12]. The construction sectors of the biggest economies of the world, such as the USA, UK, and China, are not sustainable [13]. It is estimated that the UK generates 200 million tons of waste every year, 59% of which is reported to be construction, demolition, and excavation (CD&E) waste. The people's republic of China generates around 2 billion metric tons of CD&E waste every year [14]. Therefore, the big economies must devise and implement more efficient Construction Waste Management (CWM) techniques to achieve sustainable development. There has been a lot of research on the quantification & mitigation of construction waste [15].

It is established that waste generated by construction activities harms the environment as well as the economy. Material waste also affects the financial efficiency of the project by incurring additional costs [16,17]. That is why construction waste management is the primary research objective for applying waste management options such as the reduce, reuse and recycle approach [18]. There are various sources of construction waste, but design errors, procurement, handling of materials, planning, and work methodologies are the most influential [19]. In addition to that, poorly structured sub-contracting arrangements are also a key source of construction waste [20]. Moreover, contextual factors such as poor project management tactics, untrained workforce, underprovided clarity of contract documents, and absence of quality control measures also affect waste generation and project success [21]. Greater usage of resources than planned leads to cost overruns and burdens the contingency reserve [22]. Some construction wastes are classified as natural or unavoidable wastes, which occur regardless of project type. The cost–benefit ratio of controlling such wastes is low. For example, steel reinforcement used in concrete has natural wastage of 1.91%, and the cost of reducing this wastage is more than we save. However, many potential wastes are avoidable and can be reduced by a considerable margin.

The construction industry is a key indicator of economic growth, as it drives the various segments of a country's economy due to its dynamic nature [23]. Hence, the efficiency of the construction project on the principle of sustainable development directly could enhance profits [24,25]. The construction industry needs to opt for modern innovations by improving the systematic approach, structural designs, and organizational behaviour to effectively reduce the waste of natural resources. The proper integration of digital technologies in the construction process and CWM can revolutionize traditional practices [23,26]. Therefore, this study encompasses the implications of Industrial Revolution (IR) 4.0 technologies in construction waste management. The IR 4.0 concept started with the use of automation and data exchange technologies in the manufacturing industry. It has significantly increased the efficiency of the manufacturing process by interconnecting automated machines. Similarly, the construction industry could also be enhanced by adopting IR 4.0, especially in the construction waste management (CWM) domain [3]. The industry over the next decade will witness the integration of various IR 4.0 technologies such as Building Information Modelling (BIM), artificial intelligence, airborne equipment, and smart devices that have tremendous potential to enhance the efficiency and sustainability of the construction sector, allowing prudent use of construction material and energy [27–30]. The traditional behaviour of the construction industry players often resists adopting the new technologies [31]. However, with the advent of Industrial Revolution 4.0, its importance can no longer be ignored [23].

Therefore, in context with the above facts, this study is undertaken to find the most practical and efficient IR 4.0 technologies for the construction industry from the perspective of industry professionals to reduce material waste. The construction industry is moving towards digitalisation, and to make this IR 4.0 culture successful, there is a need to highlight factors that can benefit the process. This study aims to highlight effectual factors under IR 4.0 linked technologies, which can improve the construction waste management processes. Such guidelines will give construction industry professionals confidence in IR 4.0 technologies for their implementation to control construction waste. Moreover, the identified factors have been ranked for their possible contribution to construction waste as well as the factors leading to the generation of construction waste. In this regard, a research questionnaire was designed to best meet the research objectives and built on the findings of the literature review along with the information obtained from the interviews with industry experts. The questionnaire included multiple-choice questions concerning the possible construction waste, factors that lead to the generation of waste, and IR 4.0 as a solution. A pilot survey was carried out on construction field experts. The respondents' data were then analysed by Analytical Hierarchy Process, normally called AHP, a sophisticated method used in the decision-making process. The results of this study can be very helpful in decision making while opting for the best IR 4.0 technologies to actively manage construction waste. In addition, the potential construction waste and factors leading to construction waste can be mitigated in the design, planning, and execution phases.

2. Methodology

The research mainly focuses on construction waste management through modern digital technologies such as IR 4.0 and is conducted in three main phases, as shown in Figure 1.

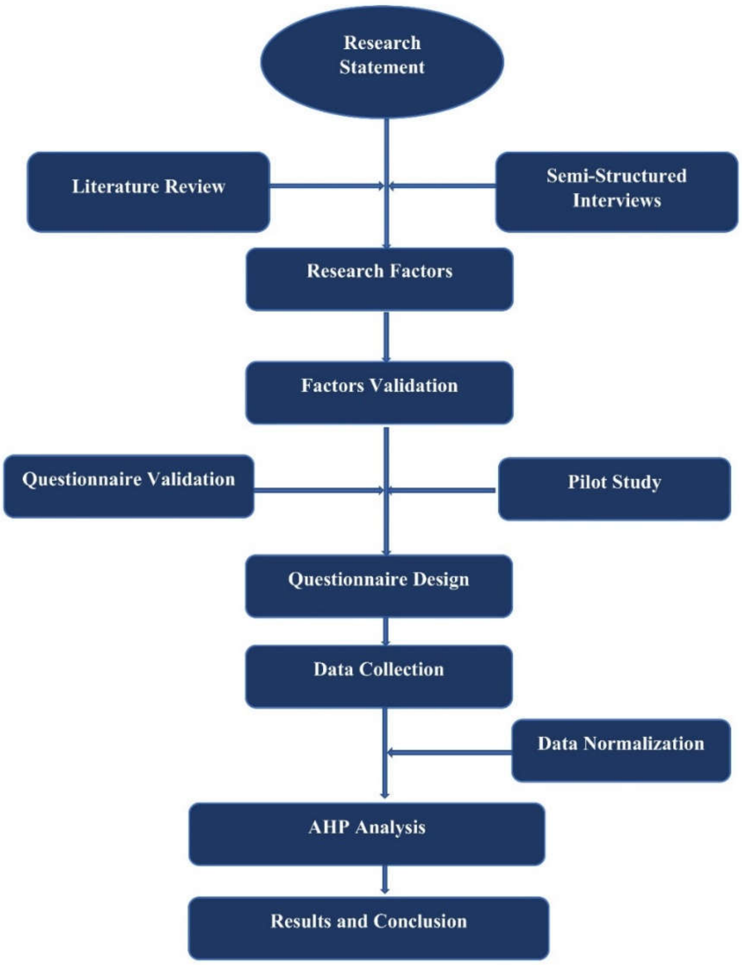

Figure 1. Research Flow.

The research objectives were designed in the first phase after conducting a comprehensive literature review to establish an understanding of construction waste and its impacts on environmental sustainability and project efficiency. Further, a series of structured interviews were also conducted with industry experts in this regard. After the cyclic process of brainstorming, examining, and modifying, assessment questions on possible construction waste were developed to check the perception of industry respondents. Furthermore, the factors leading to the generation of waste and implementation of IR 4.0 solutions were also identified. The second phase started with the development of a questionnaire coordinated with the literature review results. Afterwards, a pilot study was conducted to obtain responses from industry professionals. The respondents' data were then analysed by employing the Analytical Hierarchical Process.

2.1. Research Population

The targeted research population was mainly engineers, Contractors, Professors, and all other construction professionals. The questionnaire was distributed in commercial, residential, and infrastructure industries of Malaysia, Pakistan, India, and the Middle East, where 80% of respondents were construction site engineers.

2.2. Questionnaire Design

A research questionnaire consisting of four distinct sections is constructed based on the literature review and semi-structured interviews with the industry professionals who were well versed with the objectives of this research. All the information relevant to the research objective analysis was accumulated, examined, and formalized after iterative phases of brainstorming, modification, and research. Subsequently, a final questionnaire was formulated and distributed to obtain feedback from the industry. The format of the questionnaire was selected to be multiple choice questions. The multiple-choice questions were designed in a way to cater for the research objective first and foremost, and additionally to accumulate any relevant information that could be vital for this study along with objects and results. The questionnaire was structured in a way to obtain the respondent's knowledge of construction waste and the probable causes amplifying its generation. Further, the last part of the questionnaire inquiries about IR 4.0 solutions to minimize the waste of construction materials.

The questionnaire was divided mainly into four elaborate sections fulfilling the requirement of this study. Each section was designed consistent with the findings of prior studies. Thereafter, the factors obtained from previous studies were reviewed, modified, and then selected. The comprehensive narration of the questionnaire parts is given as follows.

Part 1: The first part consists of the respondent's general information, such as name, mail id, educational qualification, experience, etc.

Part 2: The second part consists of multiple-choice questions regarding possible construction wastes obtained through construction project execution. Based on the literature, 18 key factors were considered for questionnaire design, as shown in Table 1. Here the rating is given on a five-point Likert scale and indicated as (1) Never (2) Rarely (3) Sometimes (4) Often (5) Always.

Part 3: The third part contains the list of factors that can potentially lead to the generation of construction waste. These factors are categorized into three categories as Client-related factors, Consultant-related factors and Contractor-related factors as shown in Table 2. Each of these sub-categories consists of five (5) key factors. The factors rating is given on a five-point Likert scale and indicated as (1) Strongly disagree (2) Disagree (3) Undecided (4) Agree (5) Strongly Agree.

Part 4: The fourth part deals with IR 4.0 as a solution to minimize construction waste. Based on the literature, the factors considered for the questionnaire design are 3D Printing, BIM, Robotics and Remote technologies, Industrialized Building Systems (IBS), Augmented Reality (AR), Artificial Intelligence (AI), and big data as shown in Table 3. Here the rating is given on a five-point Likert scale and indicated as (1) Definitely not (2) Probably not (3) Possibly (4) Probably (5) Definitely.

Table 1. List of Factors of Possible Construction Wastes.

	Factors	Reference
PCW1	Wastage of sand/soil due to environmental conditions such as erosion	[32]
PCW2	Wastage of cement if stored for many days due to moisture	[21]
PCW3	Wastage of bricks due to improper utilization by the workers	[33]
PCW4	Concrete mixture is produced in excess when mixed with inappropriate volume calculation.	[34]
PCW5	Inappropriate method adoption for curing leads to wastage of water.	[32]
PCW6	Providing excess reinforcement in unwanted areas leads to waste of reinforcement bars.	[35]
PCW7	Wastage of packing materials (i.e., Paper, Cardboards, etc.)	[33]
PCW8	Wastage of wood in the formwork.	[36]
PCW9	Improper handling of bitumen leads to uneven distribution and wastage.	[21]
PCW10	Nails and screws are treated as one-time usage and are wasted.	[32]
PCW11	Wastage of Fibre in Fibre-Reinforced Concrete due to improper design mix	[32]
PCW12	In the proper shaping of the furniture, a huge amount of sawdust is produced.	[14]
PCW13	Rough handling of fragile materials leads to glass wastage.	[32]
PCW14	Improper usage of admixtures leads to wastage	[35]
PCW15	Shade nets used in the construction process are wasted/become unusable for next time	[21]
PCW16	Using unskilled workers for painting leads to paint wastage.	[36]
PCW17	Wastage of tiles while cropping and placing them.	[13]
PCW18	Improper usage of stones in the foundation leads to raw material wastage	[37]

Table 2. List of Factors Lead Toward the Generation of Construction Waste.

	Factors	Reference
	1. Client-related factors	
GCW1	Change in the order by the client/owner	[22]
GCW2	Early delivery of the construction materials	[1]
GCW3	Rushing the process without providing the required time	[38]
GCW4	Change in the purpose of the building	[22]
GCW5	Lack of finance during the purchase	[2]
	2. Consultant-related factors	
GCW6	Improper resource planning of construction materials	[1]
GCW7	Lacking proper communication between client and supplier	[39]
GCW8	Lack of site supervision	[20]
GCW9	Inability to make quick decisions	[2]
GCW10	Incorrect load report preparation	[22]
	3. Contractor-related factors	
GCW11	Handling of construction materials by untrained workers	[38]
GCW12	Inappropriate tools usage for construction materials	[39]
GCW13	Inappropriate storage of the construction materials	[18]
GCW14	Change in the site workers frequently	[20]
GCW15	Improper allotment of workers based on their experience	[38]

Table 3. List of Factors as a Solution via IR 4.0.

	Factors	Reference
	3D Printing	
IR 1	3D-Printing technology eliminates the formwork materials	[3]
IR 2	Extrusion 3D Printers greatly reduce the wastage of metals (Rebar)	[23]
IR 3	Powder 3D-Printing technology reduces powdery wastes such as cement and sand.	[4]
IR 4	Additive welding technology can be used to print the entire metal structure without wastage of steel	[23]
	Building Information Modelling (BIM)	
IR 5	BIM evaluates the building model and prevents errors that result in wastage	[40]
IR 6	BIM creates a virtual model to avoid confusion among workers and reduces inappropriate usage of materials	[30]
IR 7	BIM manages the usage of materials and helps in waste reduction	[23]
	Robotics and Remote Technologies	
IR 8	Sorting the different types of waste using robots eliminates the mixing of waste materials.	[3]
IR 9	The application of robotic arms in construction helps in the appropriate handling of the construction materials	[26]
IR 10	Radio Frequency Identification (RFID) sensors read the data in seconds, reduce time consumption and promote effective usage of materials	[23]
IR 11	Active RFID sensors allow users to obtain accurate data in real-time to eliminate transportation waste.	[23]
IR 12	In photogrammetry, sequential images are updated to reduce errors.	[23]
IR 13	The site and the material usage can be inspected from the images captured.	[41]
IR 14	Laser sensors are used to accurately predict the positions to avoid errors.	[23]
IR 15	Wind/rain sensors can be used on the day of casting on-site to eliminate wastage due to environmental conditions.	[26]
IR 16	Fibre optic sensors can be used for determining the health of the concrete.	[26]
IR 17	Strain sensors find various physical parameters such as pressure, displacement, etc., and reduce wastage from sampling.	[3]
IR 18	GPS & GIS identify places of access and storage of materials.	[23]
	Industrialized Building System (IBS)	
IR 19	Precast structures reduce the waste from the site.	[23]
IR 20	IBS reduces material wastage.	[42]
IR 21	IBS reduces crack formation which results in waste reduction.	[43]
IR 22	Panel and box system casts beams and columns, reducing on-site wastes	[44]
IR 23	Pre-fabricated timber framing systems reduce the wastage of wood on site.	[43]
	Augmented Reality (AR), Artificial Intelligence (AI) and Big Data	
IR 24	Artificial Intelligence predicts the errors earlier than their occurrence which in turn reduces the wastage.	[45]
IR 25	A combination of AI, robots and computers can synchronise trials for material selection.	[28]
IR 26	AI programs and IoT sensors are revolutionary concepts in the waste management sector.	[29]
IR 27	Big data analytics helps companies to become socially responsible and environmentally friendly.	[27]
IR 28	AR provides benefits in reducing risk and maximizing the safety of a job site	[41]
	Other Solutions through IR 4.0	
IR 29	Using decision support systems to eliminate construction wastes.	[25]
IR 30	Feedback obtained from clients using ERP helps to improve the management of waste.	[3]
IR 31	Virtual reality provides us with a virtual environment, by which errors and wastes can be eliminated.	[41]
IR 32	Life cycle assessment helps in predicting construction wastes.	[7]
IR 33	Block chain implementation helps to avoid any miscommunications and manage processes.	[41]
IR 34	Drones help in collecting digital data from sites and helps in continuous monitoring to avoid errors.	[27]

2.3. Pilot Study

A pilot study was carried out to validate the direction and understanding of the questionnaire by the respondents. Therefore, a small number of questionnaires were distributed randomly among the demographically diverse research population. Modifications were made to the questionnaire based on the feedback from the pilot study. Subsequently, the questionnaires were distributed on a large scale.

2.4. Data Analysis

The data were analysed using Analytic Hierarchy Process, normally called AHP, which is a powerful yet simple method for making decisions. It is commonly used for project prioritization and selection. AHP is a multi-criteria decision-making technique, widely adopted by researchers from many areas. The research community has shown keen interest in AHP due to its easy application. The AHP technique has also been applied in various domains covering water resources management, sustainable and renewable energy, etc., and areas other than engineering such as presidential elections, agriculture, health, climate change, etc. [46]. Generally, AHP works on three principles, decomposition, comparative judgments, and synthesis of priorities [47], which can be achieved via sensitivity analysis, decision problem modelling, valuation, and aggregation of weights [48]. AHP is a powerful tool for structuring the issues in the form of a hierarchical framework, which may take a tree shape to represent the goals. AHP can capture strategic goals as a set of weighted criteria that can then be used to score projects. The AHP is a structured technique for organizing and analysing complex decisions, based on mathematics and psychology. Microsoft Excel is employed as a tool to carry out the AHP analysis.

The consistency index (CI) using Equation (1) was also calculated. If the ratio falls below 0.10, it shows consistency in the feedback. In this case, the CI value was below 0.10 proving the consistency of the data.

$$\text{Consistency Index} = \frac{\lambda_{\max} - \text{n}}{\text{n} - 1} \tag{1}$$

where

n = Total Number of factors in an individual part
λ_{max} = Average of (Weighted Sum Value/Criteria Weights)

3. Results and Discussion

3.1. Response Distribution

A total of 300 questionnaires were distributed among the research population through email, LinkedIn, and WhatsApp platforms. The questionnaire was generated on Google Forms to obtain digital responses, which are swift and easy to analyse. A total of 108 responses were received as shown in Table 4, where it can be seen that 80% of the respondents are site engineers, 79% have a bachelor's degree, 42% have experience in the range of 5 to 10 years and 44% have executed projects for a time ranging from 10 to 20 years.

Table 4. Respondents' Profile.

S. No	Information		Frequency	Percentage
1	Education level	BE	85	79%
		MS	18	17%
		PhD	0	0%
		Other	5	4.60%
2	Position	Project Manager	5	4.60%
		Site Engineer	86	80%
		Office Engineer	10	9.30%
		Other	7	6.50%
3	Construction Work Experience	Less than 5 years	35	32%
		From 5 to less than 10 years	45	42%
		From 10 to less than 15 years	20	19%
		15 or more years	8	7%
4	Executed Projects	Less than 10	30	28%
		From 10 to less 20	47	44%
		From 20 to less 30	25	23%
		30 or more	6	6%

3.2. AHP Analysis

The Analytical Hierarchy Process (AHP) based on the evaluation criteria along with an additional set of alternative options prioritizes the best possible decision. It is pertinent to mention here that the best possible option could not necessarily justify all criteria at once, so it could be conflicting about some of the criteria. However, it is the most suitable and best fitting among all the options available. Following the decision maker's mutual comparison of the choices, the AHP assigns weightage to each of them. The higher weightage of the criteria is directly proportional to its importance. Further, in the case of a fixed criterion, a score is generated by the AHP against each option on the basis of the decision maker's comparison of the criteria. Similarly, higher score points will denote the better performance of the option given the criteria under consideration. Eventually, by combining the criteria weights and option scores, a global score and corresponding ranking are determined. The global score is the accumulated weighted sum. Here, this method is used to analyse the possible construction wastes, factors that lead to the generation of construction waste and to find the best alternative solution through IR 4.0.

3.2.1. Possible Construction Waste

The first part of the responses was related to the possible construction waste factors. The industry professionals, engineers, contractors, and academic professors rated these factors on the Likert scale as per their experiences and respective work environment. After carrying out the AHP analysis, all 18 factors were ranked. The weighted sum and rank of each factor are provided in Table 5. It is pertinent to mention here that PCW2 was ranked highest. That means, given the point of view of our respondents and based on their construction site experience, wastage of cement due to moisture is the most common and impactful construction waste. The wastage of stone in foundation and tile wastage are ranked second and third, respectively.

Table 5. Possible Construction Wastes Ranked based on the weighted sum.

	Factors	Mean	Criteria Weights	Weighted Sum	Rank
PCW1	Wastage of sand/soil due to environmental conditions such as erosion	4.03	0.0540	0.971	18
PCW2	Wastage of cement if stored for many days due to moisture	4.24	0.0568	1.022	1
PCW3	Wastage of bricks due to improper utilization by the workers	4.17	0.0558	1.004	5
PCW4	Concrete mixture is produced excessively when mixed with inappropriate volume calculation.	4.14	0.0555	0.998	11
PCW5	Inappropriate method adoption for curing leads to wastage of water.	4.14	0.0555	0.998	11
PCW6	Providing excess reinforcement in unwanted areas leads to waste of reinforcement bars.	4.17	0.0559	1.007	4
PCW7	Wastage of packing materials (i.e., Paper, Cardboards, etc.)	4.08	0.0547	0.984	17
PCW8	Wastage of wood in the formwork.	4.11	0.0551	0.991	16
PCW9	Improper handling of bitumen leads to uneven distribution and is wasted.	4.15	0.0556	1.000	10
PCW10	Nails and screws are treated as one-time usage and get wasted.	4.16	0.0557	1.002	7
PCW11	Wastage of fibre in fibre-reinforced concrete due to improper design mix	4.17	0.0558	1.004	5
PCW12	In the proper shaping of the furniture, a huge amount of sawdust is produced.	4.16	0.0557	1.002	7
PCW13	Rough handling of fragile materials leads to glass wastage.	4.12	0.0552	0.993	14
PCW14	Improper usage of admixtures leads to wastage	4.12	0.0552	0.993	14
PCW15	Shade nets used in the construction process are wasted/ become unusable for next time	4.13	0.0553	0.995	13
PCW16	Using unskilled workers for painting leads to paint wastage.	4.16	0.0557	1.002	7
PCW17	Wastage of tiles while cropping and placing them.	4.19	0.0562	1.011	3
PCW18	Improper usage of stones in the foundation leads to raw material wastage	4.20	0.0563	1.013	2

3.2.2. Factors That Lead toward the Generation of Construction Waste

The second portion of the questionnaire was inclusive of factors that can potentially give rise to material wastage. These factors were divided into three categories: client-related factors, consultant-related factors, and contractor-related factors. The respondents were asked to rate these factors on a Likert scale and the results were analysed by AHP. The factors with the highest weighted sum were ranked highest. Table 6 consists of all three categories of factors with the respective weighted sum and rank. The change orders by the client are termed as the most influential factor that can give rise to further material wastage. The re-work triggered by the design changes often results in demolition and material waste. The second and third top-ranked factors are rushing the construction process and lack of construction site supervision.

Table 6. Factors that lead toward the generation of Construction Waste.

	Factors	Mean	Criteria Weights	Weighted Sum	Rank
	1. Client-related factors				
GCW1	Change the order by the client/owner	4.45	0.0686	1.028	1
GCW2	Early delivery of the construction materials	4.25	0.0655	0.982	13
GCW3	Rushing up the process without providing the required time	4.43	0.0683	1.024	2
GCW4	Change in the purpose of the building	4.20	0.0648	0.9720	15
GCW5	Lack of finance during the purchase	4.28	0.0661	0.991	11
	2. Consultant-related factors				
GCW6	Improper resource planning of construction materials	4.36	0.0673	1.009	5
GCW7	Lacking proper communication between client and supplier	4.33	0.0668	1.001	7
GCW8	Lack of site supervision	4.41	0.0680	1.020	3
GCW9	Inability to make quick decisions	4.28	0.0661	0.991	11
GCW10	Incorrect load report preparation	4.21	0.0649	0.971	14
	3. Contractor-related factors				
GCW11	Handling of construction materials by untrained workers	4.29	0.0662	0.993	10
GCW12	Inappropriate tools usage for construction materials	4.37	0.0675	1.012	4
GCW13	Inappropriate storage of the construction materials	4.32	0.0666	0.999	8
GCW14	Change in the site workers frequently	4.30	0.0663	0.995	9
GCW15	Improper allotment of workers based on their experience	4.34	0.0669	1.003	6

3.2.3. IR 4.0 as a Solution to Minimize Construction Waste

The final part of the questionnaire inquires about the respondent's opinion regarding the most effective IR 4.0 solution. This portion was further categorized based on digital technologies i.e., 3D printing, BIM, etc. The responses were analysed similarly to the other questionnaire parts by using AHP. The analysis results are shown in Table 7, which are ranked based on the weighted sum. The analysis provides insight into the practicality of the IR 4.0 solution in the understanding of the industry personnel. The industrial building systems are found to be the highest ranked IR 4.0 solution, keeping wastage control in view. The precast building panels are manufactured in a controlled environment. Hence, the optimized process of manufacturing is helpful to control material wastage along with other benefits.

Table 7. IR 4.0 Solutions to control material Wastage.

	Factors	Mean	Criteria Weights	Weighted Sum	Rank
	3D Printing				
IR 1	3D-printing technology eliminates the formwork materials	4.39	0.0290	0.981	32
IR 2	Extrusion 3D printers greatly reduce the wastage of metals (Rebar)	4.45	0.0293	0.995	16
IR 3	Powder 3D-printing technology reduces powdery wastes such as cement and sand.	4.33	0.0284	0.967	34
IR 4	Additive welding technology can be used to print the entire metal structure without wastage of steel	4.45	0.0292	0.993	19
	Building Information Modelling (BIM)				
IR 5	BIM evaluates the building model and prevents errors that result in wastage	4.47	0.0294	0.999	12
IR 6	BIM creates a virtual model to avoid confusion among workers and reduces inappropriate usage of materials	4.51	0.0296	1.007	5
IR 7	BIM manages the usage of materials and helps in waste reduction	4.48	0.0295	1.001	10
	Robotics and Remote Technologies				
IR 8	Sorting the different types of waste using robots eliminates the mixing of waste materials.	4.45	0.0292	0.993	19
IR 9	The application of robotic arms in construction helps in the appropriate handling of the construction materials	4.40	0.0289	0.983	30
IR 10	Radio Frequency Identification (RFID) sensors read the data in seconds, reduce time consumption and promote effective usage of materials	4.42	0.0290	0.987	26
IR 11	Active RFID sensors allow users to obtain accurate data in real-time to eliminate transportation waste.	4.41	0.0290	0.985	27
IR 12	In photogrammetry, sequential images are updated to reduce errors.	4.44	0.0292	0.991	21
IR 13	The site and the material usage can be inspected from the images captured.	4.49	0.0295	1.003	8
IR 14	Laser sensors are used to accurately predict positions to avoid errors.	4.44	0.0292	0.991	21
IR 15	Wind/rain sensors can be used on the day of casting on-site to eliminate wastage due to environmental conditions.	4.52	0.0297	1.009	3
IR 16	Fibre optic sensors can be used for determining the health of the concrete.	4.46	0.0293	0.997	14
IR 17	Strain sensors find various physical parameters such as pressure, displacement, etc., and reduce wastage from sampling.	4.48	0.0295	1.001	10
IR 18	GPS & GIS identifies places of access and storage of materials.	4.47	0.0294	0.999	12

Table 7. *Cont.*

	Factors	Mean	Criteria Weights	Weighted Sum	Rank
	Industrialized Building System (IBS)				
IR 19	Precast structures reduce waste from the site.	4.49	0.0296	1.003	8
IR 20	IBS reduces materials wastage.	4.60	0.0302	1.028	1
IR 21	IBS reduces crack formation which results in waste reduction.	4.50	0.0296	1.005	7
IR 22	Panel and box system casts beams and columns, reducing on-site wastes	4.40	0.0289	0.983	30
IR 23	Pre-fabricated timber framing systems reduce the wastage of wood on site.	4.44	0.0292	0.991	21
	Augmented Reality (AR), Artificial Intelligence (AI) and Big Data				
IR 24	Artificial Intelligence predicts errors earlier than their occurrence, which in turn reduces the wastage.	4.35	0.0286	0.973	33
IR 25	A combination of AI, robots and computers can synchronise trials for material selection.	4.52	0.0297	1.009	3
IR 26	AI programs and IoT sensors are revolutionary concepts in the waste management sector.	4.51	0.0296	1.007	5
IR 27	Big data analytics helps companies to become socially responsible and environmentally friendly.	4.46	0.0293	0.997	14
IR 28	AR provides benefits in reducing risk and maximizing the safety of a job site	4.44	0.0292	0.991	21
	Other Solutions through IR 4.0				
IR 29	Using decision support systems to eliminate construction wastes.	4.45	0.0293	0.995	16
IR 30	Feedback obtained from clients using ERP helps to improve the management of waste.	4.41	0.0290	0.985	27
IR 31	Virtual Reality provides us with a virtual environment, by which errors and wastes can be eliminated.	4.44	0.0292	0.991	21
IR 32	Life Cycle Assessment helps in predicting the construction wastes.	4.45	0.0293	0.995	16
IR 33	Block Chain implement to avoid any miscommunications and manage the process.	4.41	0.0290	0.985	27
IR 34	Drones help in collecting digital data from site and in continuous monitoring to avoid errors.	4.55	0.0299	1.018	2

The possible construction waste factors assumed from the literature review and AHP analysis of responses show a practical correlation. The wastage of cement due to moisture if not stored properly was found to be the highest ranked construction waste in the result of this study, although this contrasts with some published studies, which conclude that cement and steel are the least wasted materials [36]. Conversely, this contrast is due to the demographic location and industry environment of the research population sample. Nevertheless, the results of this study stating possible construction waste shall be very useful in project construction wastage management plans. The given results of the study can be incorporated into the design, planning and execution phases of a project, enabling pro-active management of the potential construction wastes. Furthermore, this study also ranked the most influential factors that give rise to construction waste and found that a change in orders issued by the client/owner is often the main reason for construction waste. This finding is, however, in line with several studies carried out on the potential causes of material wastage [38]. Design changes are very common in the construction project, and if not managed properly by an efficient change management system can disrupt the activity sequence, resulting in huge rework and material wastage [49].

The final part of the questionnaire interrelates the possible IR 4.0 solutions that shall be employed to control the waste generated. The results in Table 4.0 show that Integrated Building Systems can be used to reduce construction waste. Pre-fabricated building modules can reduce the use of construction materials such as cement and steel significantly. Similarly, the use of prefabrication can reduce construction material waste by 25%–65% depending on the level of prefabrication work quantum [42]. There is an inverse relationship between waste generation factors and the quantity of construction waste. The optimization of root causes of construction waste can save valuable resources. Furthermore, the IR 4.0 solution has an inverse proportional relationship with the possible construction waste. The better IR 4.0 technology is employed, the better efficiency in construction waste is achieved. Based on the above discussion on IR 4.0 solutions for construction material waste control, a basic framework has been devised for illustrating an overview of the main categories along with the top two ranked factors in each, as shown in Figure 2.

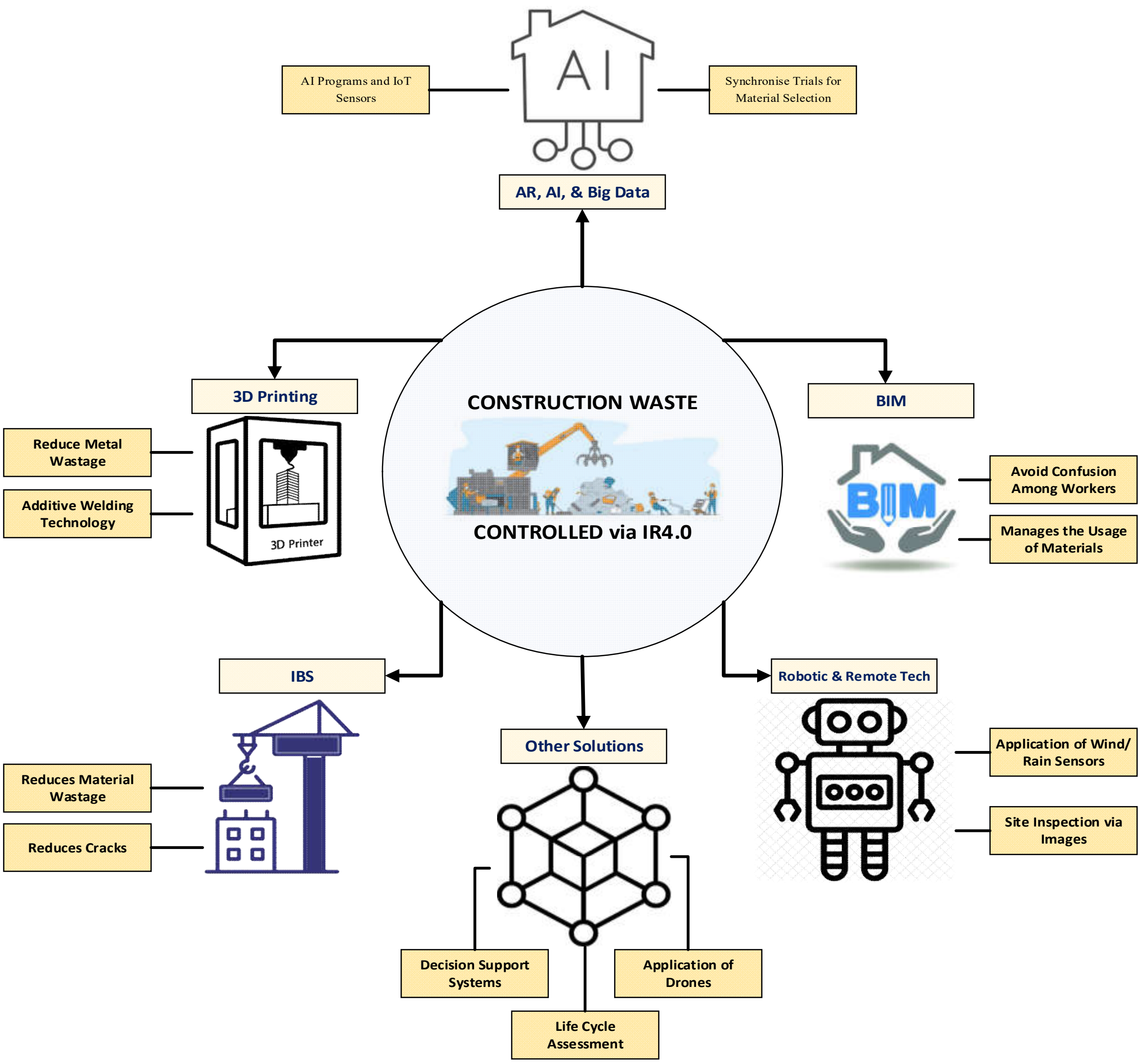

Figure 2. Basic framework for construction waste control via IR 4.0 with top ranked factors.

It can be observed that overall IR 4.0 solutions have been grouped under six main categories. However, few categories are very broad categories, i.e., containing varying technological solutions, such as categories named “AR, AI and big data”, and “other solutions”. In contrast, other categories such as, “IBS”, “BIM”, “3D printing”, and “robotics and remote technologies”, are specified solutions. This basic framework can be utilized to design and plan the IR 4.0 based solutions for construction waste material control, either adopting a specific category or a combination of categories for effective operations.

4. Conclusions

Construction waste has negative implications for project success as well as on our environment. For this purpose, this study was conducted to assess construction waste and provide a possible solution through IR 4.0. A questionnaire was developed and distributed in various regions which were then analysed through the AHP. The results of the AHP analysis show that cement wastage is a highly ranked construction waste if it is not stored properly. Similarly, change orders by the client are termed as the major factor causing construction waste, prompting rework. Further, Industrial Building Systems are considered to be the best IR 4.0 solution to manage construction waste based on the industry response. This benchmark study provides practical insight into potential construction wastes with probable triggers. The developed framework may help to understand the adoptability of IR 4.0 as a solution for construction waste management. This knowledge can be employed in the design, planning and execution phase to minimize or mitigate construction waste. Although the work was limited to issues in developing countries, the work can be extended towards underdeveloped countries too for better industrial output.

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