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Plumbing waste reduction through lean tools: A case for high-rise building construction

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Abstract
Global construction of high-rise buildings is on the rise due to the shortage of land. Plumbing work significantly contributes to the overall waste generated in high-rise construction projects. Recognizing lean tools for waste reduction in construction is essential to minimize waste generated through plumbing work. Therefore, this research aimed to propose lean tools to minimize the plumbing waste of high-rise buildings in Sri Lanka. This research adopted ontological, idealist assumptions in the interpretive paradigm for the study to collect, analyse and validate data. The data collection was done by using a qualitative approach consisting of three Delphi rounds with construction industry experts selected through purposive sampling. Manual content analysis facilitated to analyse the data. This study identified various types of plumbing waste and assessed the potential of the lean concept to mitigate waste in plumbing work during the construction stage. Just in time, 5S, Value stream mapping, Last planner system, and Frist run study were acknowledged as the most commonly used lean tools to minimise plumbing waste. There is dearth of literature on use of lean tools to reduce plumbing waste in high-rise building construction. This is one of the first studies which focus specifically on the use of lean tools to minimise plumbing waste in high-rise building projects in Sri Lanka. The findings can be further validated using case studies for similar context, which will be the next phase of this study.

Keywords
High-rise buildings, Lean tools, Plumbing waste, Sri Lanka, Waste reduction.

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1. Introduction

Cities are growing vertically as a solution to the land scarcity (Yang & Zhao, 2022; Zhong & Christopoulos, 2022). The increased demand for high-rise buildings is further attributed to the economic growth of the country and the migration of people from rural to urban areas. (Wu et al., 2020). Buildings with a small footprint, small roof area and tall façade are defined as high-rise buildings (Wang et al., 2020). In high-rise construction, Mechanical, Electrical, and Plumbing (MEP) work plays a pivotal role, accounting for 25% to 45% of the total project cost (Baradaran-Noveiri et al., 2022) and interferes with other building elements (Marzouk & Elmaraghy, 2021). MEP works are recognized as integral systems crucial for the operational performance, comfort, and safety of buildings (Korman et al., 2003). However, implementation of MEP works in high-rise buildings is challenging due to improper planning (Baradaran-Noveiri et al., 2022), price fluctuation of materials (Prasetyono & Suryanto, 2020), poor construction management (Olanrewaju & Lee, 2022) and estimating issues (Akhil & Das, 2018). Moreover, unavailability of skilled labours, scarcity of resources, high rework rate and external weather conditions shall further affect the MEP works (Wu et al., 2022). MEP works include fire detection and protection systems, air conditioning systems, vertical transportation systems, electrical systems, lighting protection systems, closed-circuit television (CCTV) systems, and plumbing work systems (Zhang et al., 2022). Among these systems, the plumbing system has a crucial function in distributing potable drinking water throughout the building (Lavikka et al., 2021). Husin (2019) emphasized that 14.1% of the overall project cost is dedicated to MEP works, with 5.3% specifically allocated for plumbing works.

Many researchers including Eldeep et al. (2022), Husin (2019) and Jalaei et al. (2021) highlighted the considerable amount of waste generated during the implementation of MEP works. The waste in MEP works has a substantial impact to time, cost and the environment (Li et al., 2019). Hence alarming the pivotal need to taking necessary actions to minimise the waste. According to Zhao et al. (2022), most of the construction waste can generate due to the design changes during the construction stage. Plumbing work in high-rise building construction always creates problems during designing, selecting components and compatibility, and installing the system (Husin, 2019). Compared to other waste in construction, waste generation from plumbing works is extensively high (Diekmann et al., 2004). Consequently, Denzer et al. (2015) proved that plumbing workers only utilise 31.5% of their working time for value-adding activities. Therefore, a need arise to implement an efficient waste management process for plumbing work (Ding et al., 2018). Previous researchers investigated waste minimization through various lenses, including the extended theory of planned behaviour (Swarna et al., 2022) and dissipative structure theory (Yuan et al., 2022). Additionally, strategies like Building Information Modelling (BIM) (Codinhoto et al., 2023) were considered as a way of reducing waste in construction. Husin (2019) stated use of lean tools such as Last Planner System (LPS), Increased Visualization, Toolbox Marketing, First Run Studies, and the 5S Process, particularly in MEP work within the construction industry, to reduce the waste.

Many countries such as United States of America (Evans et al., 2022), New Zealand (Likita & Jelodar, 2019), Saudi Arabia (Sarhan et al., 2017), Jordan (Al-Balkhy et al., 2021), Japan (Mangaroo-Pillay & Coetzee, 2022) and China (Xing et al., 2021) have used the lean concept as an effective mechanism to reduce physical and non-physical waste in construction (Babalola et al., 2019). Lean construction views lean production as a theoretical inspiration for the formulation of a new, theory-based methodology for construction that will be targeting value addition through waste minimization (Tzortzopoulos et al., 2020). Waste minimisation is one of the three pillars of the lean philosophy (Carvajal-Arango et al., 2019). Moreover, Bajjou and Chafi (2019) have demonstrated the successful application of lean principles in minimizing common barriers associated with construction waste generation. According to Koskela and Ballard (2021), the lean concept can be effectively employed as a cost-reduction technique in MEP works.

Nevertheless, most of the above research discussed lean in general and disregard types of lean tools and techniques that can be implemented to reduce waste in construction. Moreover, there is a lack of research in construction management literature focusing on reducing plumbing waste through the application of lean principles. Therefore, this study aimed to meet the industry need and literature gap to investigate the possible lean tools to reduce plumbing waste during the construction stage in high-rise buildings. The objectives of this study were to categorize the different types of plumbing waste created during the construction stage in high-rise buildings under each lean waste types, evaluate the causes of the plumbing waste generation, and investigate the lean tools to reduce plumbing waste during the construction stage in high-rise buildings. This paper shall include an introduction to the research, a comprehensive literature review, the research methodology, research findings and discussion. Finally, the conclusions and recommendations will be provided from the study.

2. Literature review

2.1. Waste in construction

In construction, waste refers to by-products of the construction process that cannot be utilized either due to non-compliance with specifications or as a result of damages and excess materials (Papastamoulis et al., 2021). Further, waste can be defined as any resource or activity that could be eradicated without maximizing customer value (Xing et al., 2021). The construction industry exerts substantial demand on natural resources and energy for building activities, generating significant volumes of solid waste while releasing toxic air (Sharma et al., 2021). Quantification of construction waste is a significant challenge faced by construction companies and the government due to the excessive generation of construction waste (Quiñones et al., 2021). Disposing of construction waste is challenging due to its hazardous components, including heavy metals, asbestos, and organic compounds (Ahmed & Zhang, 2021; Martínez et al., 2022).

Ohno (1988) has categorised waste in to seven types as over-production, transportation, over-processing, inventory, waiting, motion, and defects. Later, Womack and Jones (1996) added non-utilized talent as another type of waste. Researchers have demonstrated that these eight types of waste can also be identified in the construction industry.

2.2. Waste generated from the plumbing work

In high-rise building construction, plumbing work generates a substantial amount of waste, accounting for approximately 5.8% of the total construction cost (Husin, 2019). Plumbing waste can be generated either as materials, labour, time and cost (Seppänen & Görsch, 2022; Turner & Filella, 2021). On construction sites, not all plumbing waste can be precisely quantified. However, certain types of waste, including excess materials, labour inefficiency, and offcut material waste, can be measured in terms of value (Poreddy et al., 2015). According to the findings by Poreddy et al. (2015), it was observed that only 20-24% of the total worker's time was dedicated to value-adding tasks, while more than 40% was allocated to non-value-adding activities in plumbing work. Further, it was noted that, although plumbing work follows a standard procedure, there is no systematic way to identify plumbing waste (Claudio et al., 2009). Most of the plumbing works in high-rise buildings are done by using polyvinyl chloride (PVC) as it is free from harmful chemicals during the life cycle (Turner & Filella, 2021). However, one-third of plastic waste is PVC (Prestes et al., 2012) in construction waste which caused a massive negative impact on the environment. Table 1 presents plumbing waste identified from the construction literature.

Poreddy et al. (2015) noted that, the cost due to labour inefficiency in

***Table 1.** Types of plumbing waste.*

Plumbing waste \ Source	A	B	C	D	E	F	G	H	I	J
Process materials		✓			✓	✓	✓			
Damage materials		✓	✓	✓	✓					
Excessive materials			✓	✓				✓		
Production waste		✓	✓	✓				✓		
Rework		✓	✓	✓						
Additional fittings		✓	✓							
Defective item	✓		✓							✓
Rejected materials				✓			✓			
Low-quality materials				✓	✓					
Material idling		✓							✓	
Labour idling		✓							✓	
Double handling			✓	✓						
Additional onsite transportation		✓	✓				✓			
Additional offsite transportation		✓		✓			✓			

A-Josephson & Bjorkman, 2013; B-Kalsaas, 2010; C-Hung & Kamaludin, 2017; D-Agyekum et al., 2013; E-Husin, 2019; F- Enshassi et al., 2011; G- Formoso et al., 2002; H- Ponnada & Kameswari, 2015; I- Tommelein, 1998; J- Liao et al., 2020.

plumbing work is around 0.9%-2.93% of the total cost of the project. Waste can be generated by walking empty-handed, unplanned idle time and unnecessary movements of equipment and materials (Josephson & Bjorkman, 2013). Moreover, improper integration of pipelines and equipment may cause to generate plumbing waste, construction delays and ultimately reduce the quality of construction.

2.3. Causes for plumbing waste generation

Plumbing work may generate material waste due to changes during installation, as purchased materials, once acquired, cannot be resold or returned (Bekr, 2014). Most plumbing waste is generated due to inappropriate cutting of the pipes and poor on-site management (Ali & Hamadameen, 2020). Furthermore, Ali and Hamadameen (2020) added wrong and lack of storage of the materials and ordering excessive quantities more than required as causes for plumbing waste. Caldas, et al. (2015) revealed that inadequate planning in material distribution, lack of encouragement for cutting optimization, production of short unusable pieces when pipes are cut, and substitution of elements with superior performance are the primary causes for waste generation in plumbing work. Further, causes to generate plumbing waste were identified from literature as shown in Table 2.

Moreover, issues with communication, planning, material logistics and design are identified as major causes of plumbing waste generation (Seppänen & Görsch, 2022). Many researchers including Issa and Alqurashi (2020) pinpointed various controllable causes of waste.

2.4. Waste reduction with lean

Waste is unavoidable in construction industry (Ali et al., 2019; Koskela et al., 2007) and zero waste is unrealistic to expect from the construction industry (Moreno, 2021). Nevertheless, waste can be reduced by adopting alternative design concepts (Da-Cunha & De-Aguiar, 2020) and changing construction processes (Porwal et al., 2023). Similarly, a plethora of researchers including Ballard (2009), Ranadewa et al. (2021) and Tzortzopoulos et al. (2020) indicated the possibility of adopting lean to minimise non-value-adding activities which are synonymized for waste. The lean concept is based on three philosophies: waste minimisation, value enhancement, and continuous improvement (Bajjou et al., 2017; Hartanti et al., 2022; Koskela et al., 2007). Lean philosophy initially originated in the Toyota Production System in Japan manufacturing industry in the 1950s, and it was implemented in the construction industry after gaining full acceptance from the manufacturing industry (Jylhä, 2021; Koskela, 1992). Lean is one of the most prominent

***Table 2.** Causes of generating plumbing waste.*

No	Waste type	Cause	Sources												
			A	B	C	D	E	F	G	H	I	J	K	L	M
01	Inventory	Excess and obsolete inventory		✓	✓	✓			✓	✓	✓	✓	✓	✓	
		Overproduction		✓		✓	✓				✓			✓	
		lack of material requisition and issuance standards				✓				✓					
		High rework rates		✓		✓		✓	✓			✓	✓	✓	
02	Defects	Ordering of materials that do not satisfy the project requirement defined on the design document			✓		✓	✓		✓				✓	✓
		Incapable processes and suppliers				✓		✓							
		Unskilled workers				✓	✓	✓	✓	✓				✓	✓
03	Waiting	Interaction between various specialists		✓											✓
		Delay approval of drawing			✓		✓	✓						✓	✓
		Delay or shortage of material supply or human resources	✓		✓	✓			✓					✓	✓
		Inflexible workforce				✓		✓		✓		✓		✓	✓
		Long set-up	✓			✓									
		Poor communication	✓					✓		✓	✓	✓			
		Waiting at the quality checking area	✓				✓								
		Due to loading and unloading	✓	✓						✓					
		Deburring and inspection	✓		✓										
04	Over-processing	Unclear specification and work instructions				✓	✓	✓			✓			✓	
		Frequent changes in design and documents				✓	✓	✓		✓				✓	
		Excessive quality	✓			✓								✓	
		Failure to recognize unnecessary processing steps		✓											
		Complexity		✓			✓	✓							
		Inadequate value analysis/ value engineering	✓			✓									
05	Over-production	Volume incentives (sales, pay, purchasing)				✓									
		High-capacity equipment and machinery		✓		✓		✓							
		Poor scheduling or production planning				✓									✓
		Cost accounting practices that encourage the build-up of inventory				✓			✓	✓					
06	Transportation	Poor routine plan		✓		✓		✓							
		Distant of the suppliers		✓	✓	✓				✓			✓		✓
		Complex material flow		✓		✓				✓					✓
		Insolvent workplace organization		✓	✓				✓						
		Poor layout plan		✓		✓		✓				✓			
07	Motion	Poor layout plan		✓	✓	✓		✓					✓		
		Disorganized workplace layouts and storage locations			✓	✓		✓				✓	✓		
		Unclear or non-standardized work directives	✓			✓		✓			✓				
08	Non-utilized talent	Lack of coordination among team		✓			✓	✓	✓	✓	✓			✓	✓

Sources: A-Arunagiri & Gnanavelbabu, 2016; B-Arunagiri & Gnanavelbabu, 2014; C-Dixit et al., 2015; D-Domingo, 2003; E-Polat & Ballard, 2004; F-Nagapan et al., 2011; G-Akhil & Das, 2018; H-Luangcharoenrat et al., 2019; I-Murata et al., 2018; J-Bhatnagar & Devkar, 2021; K-Shaqour, 2022; L-Al-Balkhy et al., 2021; M-Ariyanti et al., 2021

management philosophies that consist of a large variety of tools (Ballard, 2000; Brissi et al., 2021; Howell & Ballard, 1994), which can be used to maximise the resource efficiency (Koskela et al., 2007; Naeemah & Wong, 2023; Tzortzopoulos et al., 2020). Many lean tools can eliminate waste in the construction industry as shown in Table 3.

Table 3. *Lean tools.*

Lean Tool	Brief description	Source/s
Just in Time (JIT)	Make the right items in the right place at the right time.	(Oladiran & Kilanko, 2022) (Bajjou et al., 2017)
Total Quality Management (TQM)	Increase the quality of the product to meet the expected level of customer satisfaction and production performance.	(Coelho et al., 2022) (Yusr et al., 2014)
5S method	A place for everything and everything in its place.	(Hafidz & Soediantono, 2022) (Rewers et al., 2016)
Total Productive Maintenance (TPM)	Reduce the waste linked with technological machine and equipment. Enhance the efficiency and productivity of the machines.	(Rathi et al., 2022) (Rewers et al., 2016)
Continuous Improvement	Minimise the waste and maximize the value of the activities progressively, and repetitiously that must be carried out continuously.	(Bertagnolli, 2022)
Single Minute Exchange for die (SMED)	Used to reduce the set-up time of the machine during change-over and to increase productivity.	(Ribeiro et al., 2022) (Chiarini, 2014)
Value Stream Mapping (VSM)	Graphically representing the flows of materials and information in the production process.	(Sangwa & Sangwan, 2023) (Gunaki et al., 2022)
Visual management (VM)	Provides key information effectively by displaying various symbols and tags around the organization	(Tang, 2021) (Tezel & Aziz, 2017)
Benchmarking	Compare the project performance in line with other global projects with this database.	(Alarcón & Serpell, 1996)
Last Planner System (LPS)	Facilitate the improvement of workflow and control of the production units that are carrying out individual missions at the executive level.	(Abdelmegid et al., 2021) (Boton et al., 2021)
Pull system	Handover of the project as soon as possible with the required quality.	(Akanbi et al., 2019)
Level scheduling	Process of levelling production or workload to create a stable process.	(Taghaddos et al., 2021) (Nahmias & Olsen, 2015)
Automation	Prevent generating defective products when the problem is raised.	(Prieto et al., 2021) (Rewers et al., 2016)
Gemba walk	Helps to observe a better workplace, understand the value stream, distinguish waste, and identify and correct the problem	(Babalola et al., 2019) (Ohno, 1988)
Kanban	Control inventory by providing effective inventory and record-keeping mechanisms to the construction site.	(Pekarcikova et al., 2021), (Soliman, 2020)
First run study	Prevents and mitigates the conflict and waste by conducting a prior investigation of errors and alternatives.	(Babalola et al., 2019) (Ogunbiyi, 2014)
Conference Management	Facilitates conducting conferences, workshops, and training.	(Babalola et al., 2019) (Li et al., 2016)
Fail safe for quality and safety	Take proactive action against foreseeing possible risks on the site and ensure no one on the site is harmed.	(Babalola et al., 2019)
Health and safety improvement management	Used to analyse the construction activities to address the difficulties that arise on the site.	(Babalola et al., 2019)
Teamwork and partnering	Provide an opportunity for collaboration and open exchange of information.	(Babalola et al., 2019) (Sarhan et al., 2017)

Benefits of the above identified lean tools are to eliminate non-value-adding activities, cycle time, and establish continuous improvement of the process.

2.5. Necessity of lean tools for waste reduction in plumbing works of high-rise buildings

During the past decade, construction of high-rise buildings is boomed due to the demand for high-rise buildings in Sri Lanka (Perera et al., 2020). Most often, the Sri Lankan construction industry relies on traditional procurement methods and delegates plumbing works to specialized subcontractors (Chamara et al., 2015). In the Sri Lankan construction industry, plumbing work in high-rise buildings is crucial which influences project cost overruns (Ariyawansha & Francis, 2022). This was further confirmed by

Samarasinghe et al. (2017) stating that reworks in plumbing works add an extra cost for high-rise construction and will eventually affect the delays in project delivery. Moreover, plumbing works require cognitive skills of labour which is more costly (Manoharan et al., 2022). Furthermore, Gupta and Thawari (2016) reveals that Plumbing work in high-rise buildings is one of most difficult, time consuming and expensive component of work which has a considerable waste generation. Josephson and Björkman (2013) emphasize the importance of addressing plumbing waste in the Swedish construction industry. According to Husin (2019), plumbing accounts for 5.3% of total construction costs and is a significant waste generator, requiring robust lean implementation. Seppänen and Görsch (2022) emphasized the opportunities for enhancing constructability and design coordination (20% by plumbers) as well as material logistics (10% by plumbers). However, there is a lack of research to investigate the solutions to reduce waste in plumbing work in construction industry especially for high-rise buildings.

Initially, the lean concept was confined to the automobile industry, but over time, its application has extended to various sectors, including construction, healthcare, banking, food industry and education sector (Hartanti et al., 2022; Kaswan & Rathi, 2021; Tzortzopoulos et al., 2020). Many tools have gradually developed in Europe (Spišáková et al., 2021), United states of America (Ballard, 2000; Evans et al., 2022), and Asia (Prayuda et al., 2021) to implement the lean concept in the construction industry. Even though various countries benefit from lean implementation, it is still in the developing stage in Sri Lanka (Ranadewa et al., 2021). Hettiaarachchige et al. (2022) disclosed that many structural and cultural aspects are barriers for adopting the lean concept in Sri Lanka. Conversely, the Sri Lankan construction industry faces a significant knowledge gap in waste reduction, posing a major barrier to the adoption of the lean concept (Ranadewa et al., 2021). Although past researchers such as Kilintan et al. (2022), Kumari et al. (2022), Madushanka et al. (2018), Perera et al. (2020), Saparamadu & Kumanayake (2021) had discussed the minimization of construction wastage by several approaches in high rise building projects, there is a lack of research relating to plumbing waste reduction using the lean concept in the construction stage of high-rise buildings. There is an industrial gap that exists for a way to reduce plumbing waste during the construction phase to gain a competitive advantage. Therefore, this research focused on investigating the various lean tools as potential solutions to minimise plumbing waste during the construction stage of high-rise buildings in Sri Lanka.

3. Research methodology

According to Creswell (2014), the selection of the research approach should be based on the nature of the research problem, the audience of the study, and the personal experience of the researcher. This study is required experiences and observations-based solutions from experts to implement the lean concept to minimise plumbing waste as lean implementation is not that widespread in the Sri Lankan construction industry. Therefore, this research adopted ontological, idealist assumptions in the interpretive paradigm for the study to collect, analyse and validate data. The Delphi method can be used when there is a lack of prior research which allows the interviewees to express their opinion based on the responses of the previous rounds (Hejblum et al., 2008). If the research goal is qualitative and the samples are homogeneous, less than three rounds are sufficient and yet it may be varied according to the purpose of the research (Skulmoski et al., 2007). Further, in most of the construction management-related research, a consensus was reached after two or three Delphi rounds (Moragane et al., 2022). Therefore, following the approach of Strasser (2017), this research conducted three Delphi rounds. The decision was made based on reaching data saturation, where no new insights were added, and considering the experts' agreement

Table 4. Profile of the experts.

Code	Designation	Experience in Highrise building construction (Years)	Lean Experience (years)	Related Degree (D) and/or Master's in construction (M)	Professional qualifications	Accessibility	Delphi Round 1	Delphi Round 2	Delphi Round 3
E01	MEP Quantity Surveyor	10	3	D & M	✓	✓	P	P	P
E02	Mechanical Engineer	7	2	D	✓	✓	P	P	-
E03	Quantity Surveyor	22	5	D & M	✓	✓	P	P	P
E04	Quantity Surveyor	8	3	D & M	✓	✓	P	P	P
E05	Quantity Surveyor	11	2	D	✓	✓	P	-	-
E06	Civil Engineer	12	3	D & M	✓	✓	P	P	P
E07	Mechanical Engineer	8	4	D & M	-	✓	P	P	P
E08	Quantity Surveyor	9	3	D & M	✓	✓	P	-	-
E09	Civil Engineer	10	4	D & M	✓	✓	P	P	P
E10	Quantity Surveyor	7	2	D & M	-	✓	P	P	-
E11	Mechanical Engineer	18	4	D	✓	✓	P	P	P
E12	Mechanical Engineer	15	3	D & M	-	✓	P	P	P

percentage exceeding 75%, which was deemed valid as per Sankaran et al. (2018).

The selection of participants for the Delphi rounds should consider the participants' discipline to effectively meet the aim of the research (Avella, 2016). Therefore, the purposive sampling method was selected due to the limited number of lean experts available in the Sri Lankan construction industry. Moreover, the purposive sampling method enables the inclusion of the study with rich data and helps to achieve the synthesis objectives of the study (Ames et al., 2019). The profile of the experts is presented in the following Table 4.

The chosen sample comprised individuals with over seven years of experience in constructing high-rise buildings in the Sri Lankan construction industry. Additionally, they possessed over two years of experience with lean practices and expressed a willingness to participate in the discussion.

3.1. Delphi round 1

The Delphi round one had three stages. During stage 1, it was identified the main categories and sub-categories of plumbing waste which can be generated during the construction stage of high-rise buildings. During stage 2, lean waste identified from the literature were further validated and identified the types of lean waste which can be generated during the construction stage of high-rise buildings. In stage 3, the generic causes and sub-causes of plumbing waste generation were identified.

3.2. Delphi round 2

The Delphi round two had four stages. In stage 1, plumbing waste were categorised. During stage 2, the identified plumbing waste were categorised into lean waste types. In stage 3, identified causes and sub-causes of plumbing waste generation were categorized according to the lean waste types. During stage 4, identified lean tools from the literature were further validated to reduce the plumbing waste generation during the construction stage of the high-rise building.

3.3. Delphi round 3

During the Delphi round three, the researcher further investigated the lean tools which can be used to reduce the plumbing waste generation in high-rise buildings during the construction stage.

3.4. Data analysis

Content analysis can be defined as "a detailed and systematic examination of the contents of a particular body of materials for identifying patterns, themes, or biases" (Leedy et al., 2014). Therefore, content analysis was the most suitable data analysis technique for this study as it provides the opportunity to communicate the experts' opinions through the texts and easy to shows the relationship between the lean concept and plumbing waste reduction. Nvivo12 used to aid the content analysis process.

4. Research findings

4.1 Identification of plumbing waste in high-rise buildings during the construction stage (Delphi round 1 stage 1 [DR1S1] and Delphi round 2 stage 1[DR2S1])

Four main categories and fourteen sub-categories of plumbing waste from the literature were confirmed during DR1S1. In addition, mismatched fittings and unnecessary onsite transportation have been introduced by experts as another two sub-categories of plumbing waste which can be generated in high-rise buildings during the construction stage. During DR2S1, the experts' explanations led to the identification and categorization of sixteen sub-categories of plumbing waste into four distinct categories, as illustrated in Figure 1.

E01 explained mismatched fittings are also material waste as they cannot be resold or returned to the supplier. E02 revealed that rework is attributed to human errors, communication issues, design changes, and the use of low-quality materials, leading to the generation of waste in terms of time, materials, and labour. According to E02, E03, and E06 stubborn workforce also can affect labour waste. E03 further explained, "*less workforce involves in the plumbing activities in a particular time. Even a single person's contribution will be counted as a higher fraction. Therefore, it is important to resource-levelling schedule with better planning*". Moreover, unnecessary onsite transportation has been identified as another sub-category of labour waste.

4.2 Categorisation of plumbing waste into lean waste in high-rise buildings (Delphi round 1 stage [DR1S2] and Delphi round 2 stage 2 [DR2S2])

Among the eight types of lean waste identified from the literature, seven types were identified during DR1S2. All the experts have agreed that the waste generated in the construction phase cannot be categorized as overproduction waste. Further, in

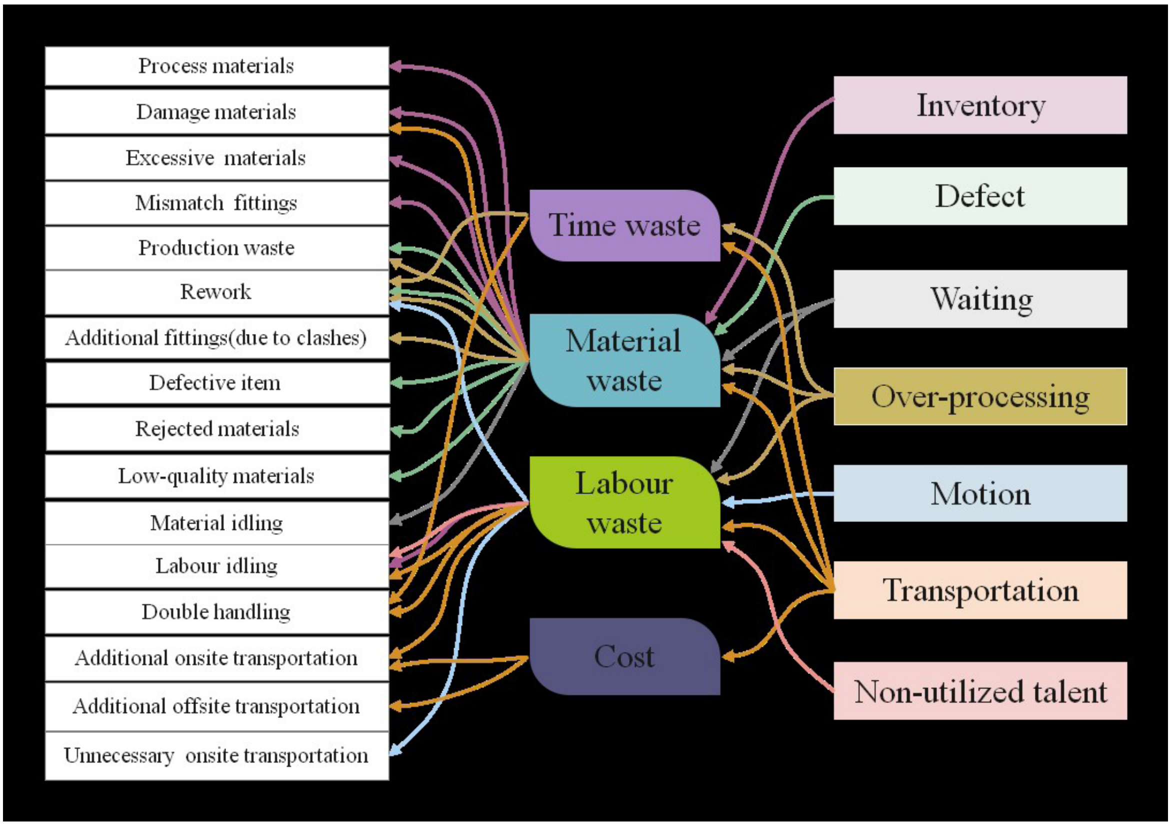

Figure 1. *Types of plumbing wastes.*

DR2S2, identified main categories and sub-categories of plumbing waste have been categorized into the lean types of waste identified in the literature as illustrated in Figure 1.

Inventory, over-processing, defects, waiting and transportation are the main types of material plumbing waste that can be produced during the construction of high-rise buildings. Process materials, damaged materials and excessive materials are generated due to materials being in inventory at construction sites. Labour waste is the main type of waste that is generated under motion and non-utilized talent waste. During plumbing activities on the construction site, labour idling is a common occurrence, often attributed to poor communication, delays in approvals, and material supply. Additionally, plumbing activities contribute to time and cost waste on the construction site. Over-processing and defects waste are produced due to the high rework rate in plumbing activities. Given the numerous sanitary appliances involved in plumbing work, special precautions are necessary during their delivery to the construction site. E07, E06 and E11 emphasized that many high-rise building constructions face challenges with long-distance suppliers and complex material flow. They further stated that, importing materials and sanitary appliances from foreign countries can result in delays and potential shipping damages, impacting project timelines. Hence, material, labour, time and cost waste can be categorized under transportation lean waste.

4.3 Causes for plumbing wastes during the construction stage of high-rise buildings (Delphi round 1 stage 3 [DR1S3] and Delphi round 2 stage 3[DR2S3])

Among identified 34 generic causes of lean waste generation from literature, 30 causes were identified as the causes of plumbing waste generation during the construction stage of high-rise

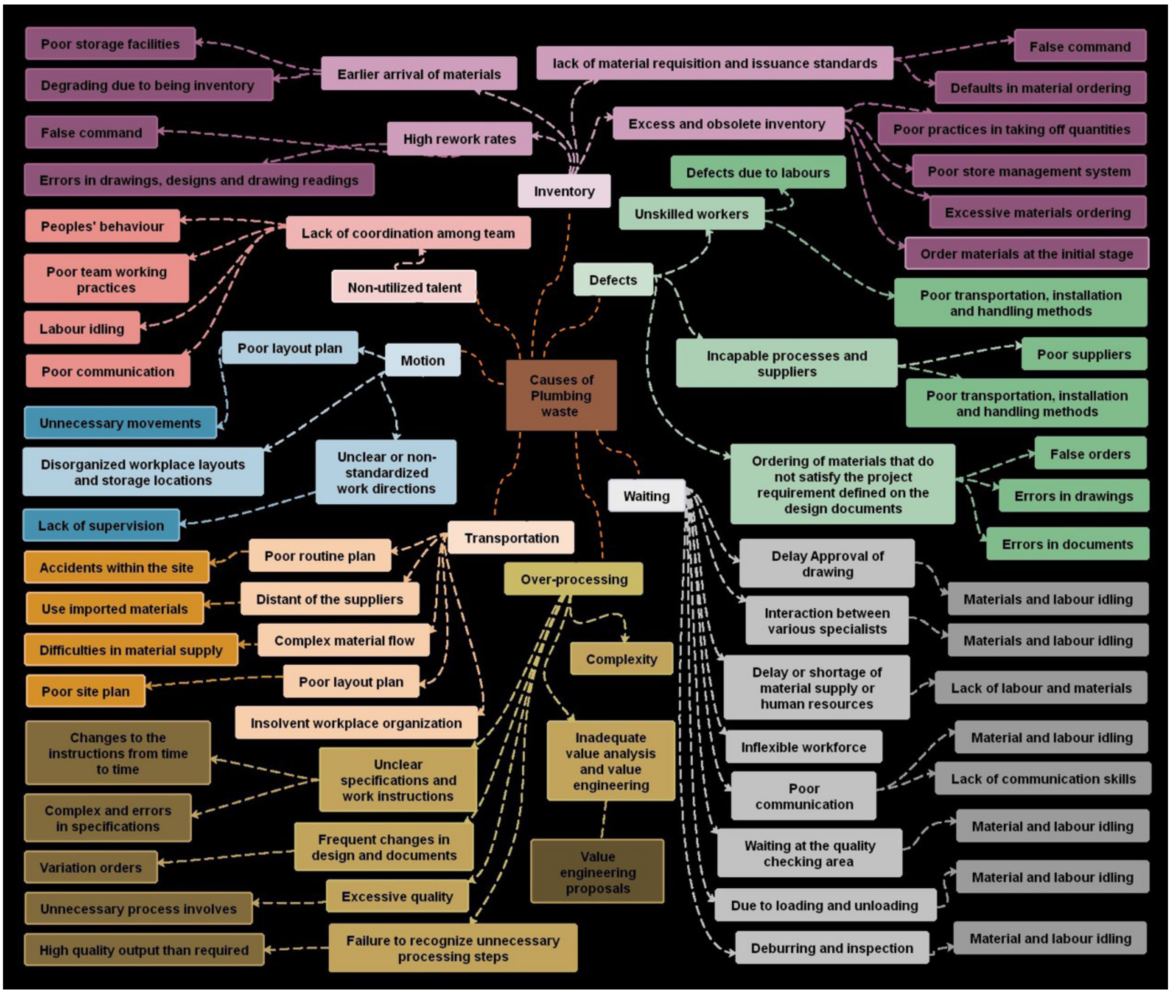

Figure 2. *Causes and sub-causes of plumbing waste generation.*

buildings in DR1S3. Moreover, earlier arrival of material has been identified as one of the major causes of plumbing waste. In addition, sub-causes under each cause were identified by the experts as shown in Figure 2. In DR2S3, identified causes and sub-causes were categorized according to the seven lean wastes.

E01 has indicated that the "*earlier arrival of the materials*" is also one of the major reasons for the inventory type plumbing waste generation. All the other experts also agreed with respondent E01. E03 highlighted that a significant contributor to plumbing waste is the need for reworking, often caused by identifying leakages and failures after the finishing stages. E07 mentioned that there may be frequent changes in design and documentation due to adherence to traditional procurement methods in the Sri Lankan construction industry. E09 reiterated that professionals in the Sri Lankan construction industry are hesitant to embrace the design and build procurement methods due to concerns related to cost and time constraints. On the other hand, E04 and E07 mentioned that lack of technical skill as the main reason for waste generation in the plumbing work. E07 highlighted that due to the lack of knowledge and poor handling methods, defects can be occurred in plumbing work. One of the major reasons arises waiting waste is the conflict between parties. All the experts agreed that "*poor Communication*" as the reason to arise conflict between parties. E01 and E04 mentioned that flexibility of the workforce also can affect waiting. This is further explained by E03 stating "*Resource levelling for plumbing activities is crucial due to limited workforce involvement at specific times. Each individual's contribution carries significant weight, emphasizing the need for careful planning in the scheduling process*". High-rise building constructions involve long-distance suppliers and intricate material flow, leading to potential delays and shipping damages. E07 highlighted the need for re-ordering materials due to poor quantifications. Experts unanimously pointed to lack of coordination as a key factor in underutilizing available personnel for the work.

4.4 Lean tools to minimise the plumbing waste according to lean waste types (Delphi round 2 stage 4 [DR2S4] and Delphi round 3 stage 1 [DR3S1])

Twenty numbers of lean tools that can be implemented to reduce construction waste were identified

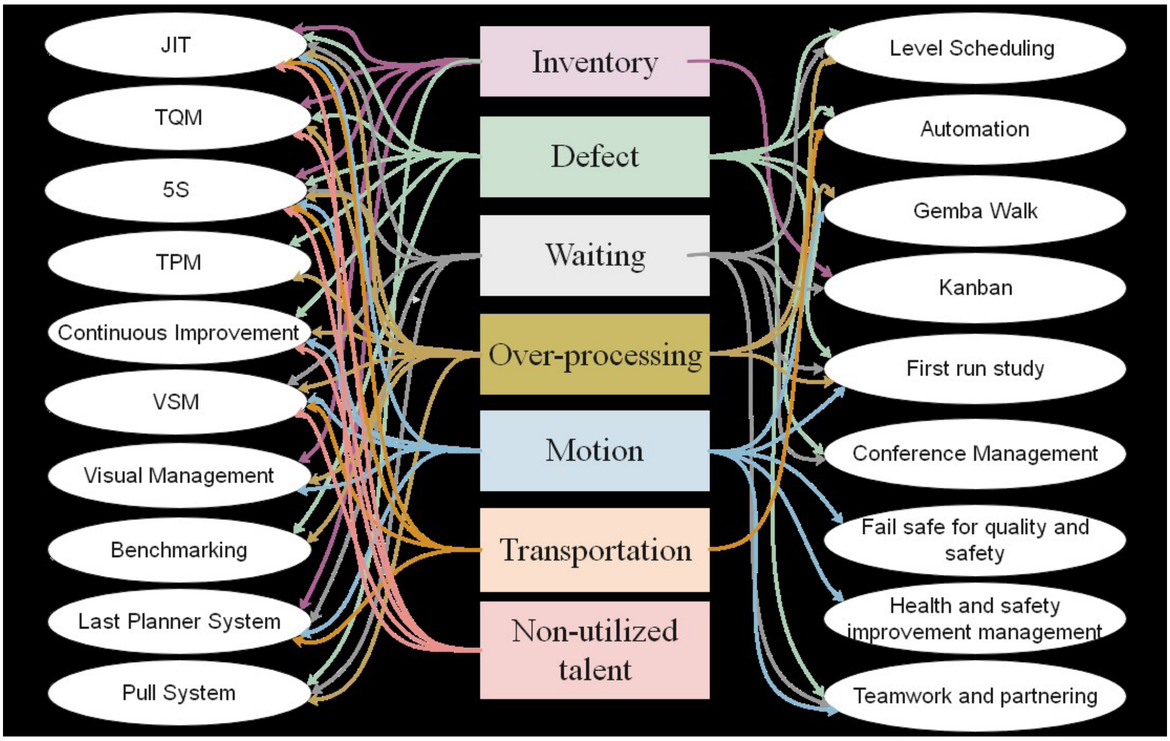

Figure 3. *Lean tools to reduce plumbing waste.*

during the literature review. These lean tools were scrutinized during DR2S4 to reduce plumbing waste. Except for single minute exchange for die tool, other nineteen tools were identified as tools to minimise plumbing waste. In DR3S1, the proficiency of each lean tool to minimise the plumbing waste was further investigated as per the lean waste types. The findings were summarized as illustrated in Figure 3.

In plumbing work, material waste can be generated due to inventory, defects, waiting, over-processing and transportation. According to experts, Just in Time (JIT) is the most appropriate lean tool to reduce material waste caused by inventory. This was further confirmed by E03, stating "*JIT as an inventory management tool*". According to E07, 5S method can be used to inventory management by optimizing inventory levels and removing unnecessary clusters. According to E09's explanation, "*LPS provides a better link between workers and the workflow. Hence, it directs the workers through continuous learning and corrective actions*". All the experts have agreed with the Value Stream Mapping (VSM) as a tool to reduce material waste. E01 highlighted that the VSM offers a chance to comprehend the information flow in construction, effectively minimizing materials waiting.

Labour waste can be generated due to waiting, over-processing, motion, transportation and non-utilized talent. According to the experts' Total Quality Management (TQM) minimise labour waste in plumbing works. As indicated by E07, "*TQM is a quality control tool. While improving the quality, the construction should reduce the unnecessary process also.*" Similarly, E06 emphasized the need to streamline plumbing installation processes, given the limited human resources involved, to minimize unnecessary steps. E01 and E03 highlighted that the 5S method can decrease labour idling by identifying unnecessary workers promptly. Additionally, E09 supported the use of VSM to mitigate labour waste in plumbing work.

In plumbing work, time waste can be generated due to over-processing and transportation. According to E01's explanation, JIT time shall consist of the ability to manage the logistics of the building workforce, materials, and equipment on the construction site. Building upon E01's insight, E07 emphasized the advantages of JIT delivery in the often-congested nature of the construction industry, highlighting its positive impact on project delivery. E04 indicated that LPS eliminate the time waste on plumbing activity. As highlighted by E03, the automation of construction projects, especially those using BIM and Cyber-Physical System (CPS), creates a more streamlined working environment. Automation, particularly in plumbing, efficiently handles material import, managing transportation and freight aspects, thereby preventing time wastage. E09 underscored that the First Run Study can mitigate time waste in plumbing works by creating a mock-up model before commencing installation. This approach facilitates the identification of optimal construction processes, streamlining the plumbing workflow.

In plumbing work, direct cost wastage through transportation can be curtailed by employing VSM. E08 emphasized that VSM not only serves as a communication tool but also functions as a change management and strategic planning tool by identifying non-value-adding activities. Additionally, automation can effectively diminish the cost of waste by detecting clashes, preventing reworks, and enhancing the quality of work.

5. Discussion

During this study, different plumbing waste and causes of plumbing waste generation were identified. Further, suitable lean tools to reduce plumbing waste were identified from the research. Even though Pieńkowski (2014) and Vaz-Serra et al. (2021) identified overproduction as a waste type in plumbing work, the experts of the study have not identified overproduction as a type of waste generated from the plumbing work during the construction phase. The experts of the study reasoned stating that, production process of plumbing items is not related to the construction process.

During the data collection, material waste has been identified as one of the major types of waste generated during the plumbing work construction. Materials such as sanitary fittings, wrapping, timber pallets, crating, and joint sealant were recognized as sources of waste during construction, emphasizing the need for additional allocation (Lam et al., 2019). Researchers including Agyekum et al., (2013), Hung & Kamaludin (2017) and Salgin et al. (2016) have identified causes of lean waste during the construction stage. The experts in this research study concurred with the causes outlined in the literature, such as high rework rates, additional fittings, and production waste. Earlier arrival of the material has been identified as one of the major causes of inventory waste generation during the data collection. Furthermore, Akhil and Das (2018) mentioned that early arrival and delay in material lead to various problems in plumbing work.

Lean tools such as 5S method, Continuous Improvement, VSM, Level Scheduling, Automation, JIT, Kanban, Total Productive Maintenance, Gemba walk, Teamwork and partnering, and Visual Management have been identified as lean tools that can be implemented for plumbing waste reduction by many researchers including Leksic et al. (2020), and Purushothaman et al. (2020). Benchmarking (Babalola et al., 2019), Pull system (Akanbi et al., 2019; Babalola et al., 2019), LPS, first run study, TQM, Conference Management, Fail-safe for quality and safety tools also can successfully be integrated to the construction stage to reduce the plumbing waste generation (Babalola et al., 2019), validating the literature finding on types of lean tools that can be used to reduce the plumbing work. JIT can provide resources only when they are needed (Bajjou et al., 2017) and 5S method does not require a high initial investment (Rewers et al., 2016). Therefore, experts of the study identified JIT and 5S method to eliminate all lean waste during plumbing work. Nevertheless, it is required to conduct longitudinal studies to analyse the suitability of implementing JIT and 5S to reduce the plumbing waste. JIT helps to minimise material waste, prevent over-processing and defects caused by being inventory for extended periods by ensuring that materials are delivered to the site on time. Further, 5S method aids to organise the construction organisations efficiently, maintain cleanliness and standardize workflows. Therefore, it is crucial to delve into additional research on the application of lean tools for minimizing plumbing waste in high-rise building construction. The study has pinpointed various lean tools for this purpose, emphasizing the need for future investigations into their long-term impact and sustained effectiveness in reducing plumbing waste in high-rise building projects in Sri Lanka.

The findings further confirmed the need of automation to reduce the lean waste. Therefore, exploring the integration of advanced technologies such as BIM and CPS for real-time monitoring and waste reduction is an area of significant interest. Therefore, the findings of this research can be used as the foundation to conduct research on BIM implementation for plumbing waste reduction in high-rise building construction. Moreover, comparative studies between different high-rise projects and the adaptation of lean principles in diverse construction contexts can be conducted based on the findings of the study. Moreover, exploring the socio-cultural factors that impact lean practices in order to minimize the identified waste from the research and evaluating the scalability of lean strategies in the wider construction industry could serve as potential avenues for future research.

6. Conclusion and recommendations

This study aimed on investigating the possible lean tools in reducing plumbing waste during the construction phase of high-rise buildings. The research underscores the significant influence of plumbing waste in the construction of high-rise buildings, specifically during the construction phase. It delineates 16 distinct waste types spanning material, labour, time, and cost categories. These identified wastes were then correlated with each corresponding lean waste type. It's worth noting that the primary focus of the research did not include overproduction lean waste, as it predominantly occurs in the production of plumbing items rather than on-site construction.

Further, a total of 30 causes and 41 sub-causes of plumbing waste were identified and categorized based on the seven lean wastes from the research. The research has proven that excluding the single-minute exchange for die lean tool, the other 19 identified lean tools, such as JIT, 5S, VSM, LPS, TQM, continuous improvement, and first run study, can be strategically implemented to eliminate plumbing waste in the construction stage of the Sri Lankan construction industry. Hence, the findings of the study provide valuable insights for industry professionals seeking to select the most appropriate lean tools for minimizing plumbing waste in high-rise building construction. This research contributes to enhancing safety, optimizing process flow, and boosting customer satisfaction in plumbing operations by identifying specific wastes associated with plumbing work.

The lean concept is unconventional to the Sri Lankan construction industry. Therefore, this study has contributed to enhance the knowledge about the lean concept, lean tools, plumbing waste types, and the cause of plumbing waste generation of respective lean waste, identifying the possibilities to implement lean tools to reduce the plumbing waste generated in the construction stage. Based on the comprehensive categorization of plumbing waste and the causes, it is recommended to incorporate lean principles and tools into the project planning phase to proactively address potential sources of plumbing waste. The findings further recommended the importance of collaboration and communication among different stakeholders involved in high-rise building construction as it helps in reducing errors, delays, and rework, which are significant contributors to plumbing waste. Moreover, it is recommended to collaborate with industry associations and regulatory bodies to develop and promote industry-wide guidelines for plumbing waste reduction as the standardization of activities can provide an implementable framework for construction projects to align with lean principles.

Additionally, it is advisable for the construction industry to launch educational programs focused on increasing awareness about the advantages of implementing lean practices in plumbing work. This includes training programs for construction professionals to gain a broader understanding of lean tools. Moreover, it is recommended to establish benchmarks and best practices based on successful case studies and projects. By incorporating these suggestions, the construction industry can make a substantial impact on reducing plumbing waste and enhancing overall efficiency, leading to a reduction in overall waste and an improvement in the sustainability of high-rise building projects. Ultimately, this will contribute to the increased sustainability of the project, fortifying the construction industry's resilience and promoting a more sustainable future. Additionally, it will foster socio-cultural improvements within the construction industry.

This study was limited to the construction stage of high-rise building projects in construction organizations. This is one of the first studies which focus specifically on the use of lean for plumbing work in high-rise building projects in Sri Lanka. The findings can be further validated using case studies, which will be the next phase of this study. This study will be useful to benchmark for future research studies in other countries as well.

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