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Reducing construction waste: A study of urban infrastructure projects

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ABSTRACT

The construction industry is well-known for producing waste detrimental to the environment, and its impacts have increased with the development process of cities. Although there are several studies focused on the environmental impact of residential and commercial buildings, less knowledge is available regarding decreasing construction waste (CW) generation in urban infrastructure projects. This study presents best practices to reduce waste in the said projects, stressing the role of decision-making in the design stage and the effective management of construction processes in public sector. The best practices were identified from literature review, document analysis in 14 projects of urban infrastructure, and both qualitative and quantitative survey with 18 experts (architects and engineers) playing different roles on those projects. The contributions of these research are: (i) the identification of the main building techniques related to the urban design typologies analyzed; (ii) the identification of cause-effect relationships between the design choices and the CW generation diagnosis; (iii) the proposal of a checklist to support the decision-making process, that can be used as a control and evaluation instrument when developing urban infrastructure designs, focused on the construction waste minimization (CWM).

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1. Introduction

The construction industry is well-known as a source of negative environmental impacts, which are associated with both the production and the extraction of raw materials, and the execution of its projects. Some of the most significant impacts caused by the sector are linked to the generation of construction waste (CW), which, according to Solís-Guzmán et al. (2009), has been more and more significant due to the accelerated growth of cities (Yang et al., 2017). In Brazil, around 45 million tons of CW were produced in 2015, which is equivalent to 57% of the total solid waste produced in the country (Abrelpe, 2015).

The waste disposal in large urban areas causes problems such as the degradation of the urban landscape (Shen and Tam, 2002; Bakshan et al., 2017). Furthermore, waste disposal is associated with soil and water contamination, due to the discard of dangerous materials, such as asbestos and volatile organic compounds – VOCs (Esin and Cosgun, 2007).

In this context, urban infrastructure projects, due to their nature – such as the extensive area of intervention and excavation services – are large CW generators. Therefore, the development of construction projects with less environmental impact is a major improvement opportunity, especially regarding decision-making at the design stage, which allows the control of CW at its source (Ekanayake and Ofori, 2004; Esin and Cosgun, 2007; Esa et al., 2017; Song et al., 2017; Yang et al., 2017). However, as highlighted by Li et al. (2015), in many cases, designers lack the proper knowledge and tools for making-decisions informed by environmental criteria.

Thus, it is important to design strategies aiming at both processes and products to be streamlined, contributing to the reduction of environmental impacts on construction stage of urban infrastructure. For example, Lean Construction (LC) and green building methods may constitute appropriate approaches to developing projects with less environmental impact, especially considering the reduction of materials waste (Nahmens, 2009; Udawatta et al., 2015). Although there are several environmental certifications guiding building designs, methods for environmental assessment in projects of urban infrastructure are quite superficial or even inappropriate (Wang et al., 2015). Indeed, these methods disregard the dynamic relationships among design strategies and the determinant factors to the construction waste minimization (CWM). Besides, there is no reliable database to support a proper diagnosis of waste generation at urban construction, as well as there is not a complete understanding of the relationship between the causes of that generation.

Thereby, this article aims to identify the best practices to reduce the construction waste in the design stage of public urban infrastructure projects. As a result, the following items are discussed: (i) the main building techniques related to urban design typologies analyzed; (ii) the cause-effect relationship between the design choices factors and the characterization of CW generated; and (iii) the checklist to support the decision-making process, that can be used as a control and evaluation instrument at development of urban infrastructure projects, focused on the CWM.

This paper is divided into five sections. Section 1 contextualizes the research problem and the paper goals. Section 2 deals with the literature review, addressing causes of CW generation and mechanisms for its minimization. Section 3 presents the method, while Section 4 brings the results and its deployments. Finally, Section 5 presents the conclusions and some research opportunities.

2. Materials waste

The generation of CW may be linked to many causes like design decisions, construction planning, execution problems, among

others. In design stage, unforeseen changes in design, insufficient detailing and flaws in product specification, besides the poor communication between the team of the project, are considered significant causes of materials waste (Osmani et al., 2008; Al-Hajj and Hamani, 2011; Liu et al., 2015).

During the construction stage, the materials wastes are related to factors such as transportation damages, improper handling, excess offcuts caused by unskilled labor, unplanned storage, and weather (Lingard et al., 2000). Formoso et al. (2002) performed a mapping of both direct and indirect material waste causes of different types of common building materials in Brazilian constructions, pointing out recurrent problems related to the lack of design standardization (Li et al., 2015; Esa et al., 2017); lack of modular coordination (Udawatta et al., 2015); poor integration between subsystems; insufficient planning site layout (Nagalli, 2014); and lack of resources optimization.

In addition, some materials are the highest waste generators than other by their own nature (Nagalli, 2014; Hassan et al., 2015; Song et al., 2017), especially in its volume CW generation per square meter built (m^3 of waste/ m^2 built), such as concrete, mortar, bricks, steel and ceramics/tiles. In some studies, it was also highlighted the earthmoving work, the excavations and the initial cleaning of land as waste sources (Jaillon et al., 2009; Solís-Guzmán et al., 2009; Katz and Baum, 2011; Marrero et al., 2017). Jaillon et al. (2009) emphasizes the expressive wood waste amount in its use on timber formworks, resulting in around 70% in increase of CW production.

The actions taken to reduce damages are the key to minimizing the waste generation; both in design and construction stage. This issue can be solved by different perspectives. Regarding the material waste minimization in design stage, Saez et al. (2013) identified the best practices to be adopted by the design team such as the massive adoption of prefabricated systems; the use of recycled materials at the construction site; and the construction site planning, observing the availability of adequate area to waste management.

Another current approach is the adoption of Lean Construction principles and practices in both project management and construction, since the LC is based on the notion of processes continuous improvement, focusing on waste reduction (Marhani et al., 2013). The LC can also help to minimize rework in managing the design stages, through the implementation of Building Information Modeling tool – BIM (Cheng and Ma, 2013; Li and Yang, 2014; Alwan et al., 2017; Ajayi et al., 2016; Won et al., 2016); schedule monitoring methods and pull planning (Ghosh et al., 2014). According to Ghosh et al., 2014, by means of the adoption of LC, the design team can detail more precisely many components, reducing approximately 6% in the waste generation at source.

Given those impacts, both economic and environmental, this article intends to show some studies developed to support the reduction on CW generation in urban infrastructure projects.

3. Method

This study is structured into four steps, as shown in Fig. 1, and detailed next.

3.1. Main building techniques of urban infrastructure designs

The first step was the identification of the main building techniques associated with the studied design typologies. For that purpose, we analyzed budgetary compositions and technical specifications pricing systems officially released by the Brazilian Federal Government namely: State Department of Budget and Constructions (ORSE), Table of Price and Compositions for

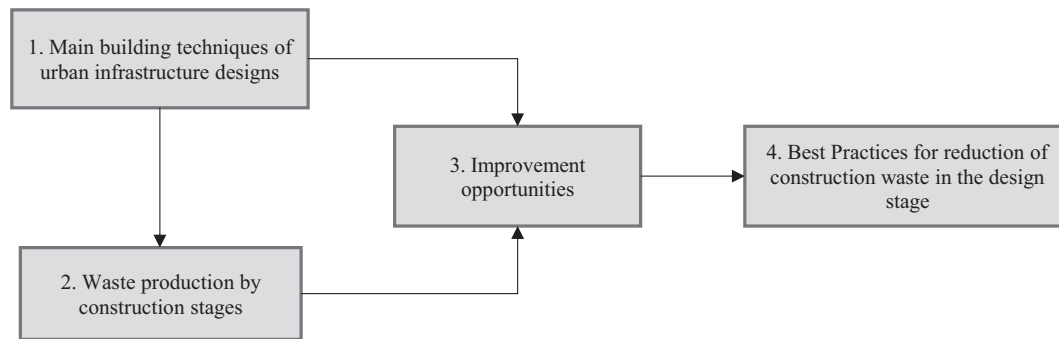


Fig. 1. Research steps.

Table 1

Main characteristics of the analyzed projects.

| No. | Project | Built area (m ²) | Period (months) | Status |
|-----|---------|------------------------------|-----------------|-----------|
| 1 | A | 1315.00 | 6 | Ended |
| 2 | B | 5245.00 | 12 | Ended |
| 3 | C | 280.00 | 7 | Ended |
| 4 | D | 6000.00 | 5 | Ended |
| 5 | E | 3446.30 | 26 | Ended |
| 6 | F | 879.50 | 7 | Ended |
| 7 | G | 9798.59 | 6 | Ended |
| 8 | H | 440.00 | 3 | Ended |
| 9 | I | 3216.00 | 30 | Bidding |
| 10 | J | 19,830.68 | 36 | Licensing |
| 11 | K | 2035.22 | 16 | Licensing |
| 12 | L | 574.45 | 7 | Running |
| 13 | M | 7448.00 | 8 | Running |
| 14 | N | 5730.00 | 12 | Running |

Estimates of Costs and Bidding (TCPO) and Brazilian National System of Indexes and Pricing for Construction (SINAPI). The collected data were crossed identifying the main types of urban infrastructure designs. For each type of the design, the main construction practices were characterized, including the building techniques employed.

3.2. Waste production by construction stages

Concerning step 2, it involved the identification of waste production by construction stages. Thus, this study analyzed 14 urban infrastructure projects of a public university, as Table 1 presents. Out of those projects, eight were already executed, three were in progress, and three were not yet implemented, being in licensing or bidding stage. The data sample was performed both qualitatively and quantitatively, considering the last two years (2014–2016).

In this step, it was made the identification of the main five building techniques employed for each single type of design. It was considered its level of use as well as its economic importance in relation to the total budget of the construction. Strategically the main five building techniques were analyzed, considering their percentage cost, since their sum represents, for each type of the design, at least 60% of the total budget of the constructions. The correspondence between the types and the quantities of CW produced was made through three documents' analysis including the spreadsheet of waste transport control, Manifesto of Construction Waste Transport of Porto Alegre, and spreadsheets of payment of the service measuring that contains data relating to items removal and waste disposal. There were also considered the quantities and types of CW provided by the Construction Waste Management Plans, which were integral part of each analyzed projects.

3.3. Improvement opportunities

Based on previous data obtained, it was started the third step (identification of improvement opportunities) in order to reduce the CW generation. That step of the research was carried out through the application of both qualitative and quantitative surveys, by the use of questionnaires. The first one made of open-ended questions and the second contained prioritization questions. The survey has been applied to urban infrastructure project professionals, active in variety sectors, and at different career levels. They included 18 professionals, out of which 13 (72%) working in public companies, and five (28%) working in private companies, with a seven-year average of time experience in the market. Among them, there were 50% of architects, 40% of civil engineers, and 5% of both agronomist and environmental engineer. According to their professional roles, the experts were classified as designers (50%), project managers (28%), building inspectors (17%), and environmental analyst (5%). The survey was conducted with distinct professionals to obtain, for the same problem, different viewpoints and technical requirements.

In this step, a pre-test questionnaire was conducted to identify possible problems of interpretation. Subsequently, since there were no changes to be done, it proceeded with the two-phase questionnaire, sent by e-mail. The first phase took place between March 9th and 18th, 2016, and the second, between March 24th and 31st, 2016.

The questionnaire had five open-ended questions involving the following topics: what strategies each professional consider appropriate to use at the design stage to reduce the CW generation, potential factors that prevent or hinder the implementation of such strategies, main causes of waste generation in construction stage, the most usually employed building techniques by each professional in the urban designs analyzed, and from a given list, which techniques they consider can cause lower and higher waste generation for each type of design. The responses from questions one to three were grouped by affinity and they were allocated to the experts' professional area. In questions four and five, the respondents could mention as many techniques as wanted and, on the last question, they should also identify at least, two building techniques as larger waste generators and other two as lower waste generators for each design type.

In the second phase of the questionnaire application, the obtained answers in questions one to three were organized into a list, and it was asked the experts to quote the five most important among them. Each participant received a list randomly organized, to prevent any bias in their choices. The importance scale adopted to rank the items ranged from one (most important) to five (least important). To calculate the resulting importance, we derive the reciprocal of the response value (1/response value) such that the very important response (1) will have a maximum value of 1

(1/1) and the least important response (5) will have a low value of 0.2 (1/5).

Thereby, all of the responses were ranked according to their importance. The strategies obtained in question one were related to the typical design stages in order to verify their application. The design stages were defined by documentary analysis of the recommendations of two Brazilian Federal Government's control agencies (SEAP, 2014; TCU, 2014).

3.4. Best practices for reduction of construction waste in the design stage

The step of the best practices identification was based on the literature review of both waste reduction recommendations and the tools of LC system, diagnosis of the projects regarding waste generation studied in step 2; as well as experts' opinions, collected in step 3. The best practices were categorized into six types according to their origin, namely: strategies (S), derived from the survey with experts; barriers (B), which are best practices admitted as solutions for implantation barriers, mentioned by the experts; guidelines (G), which derived from other researchers' studies; application of Lean Construction practices (LC), which best practices are derived from the techniques of this system's use; Leadership in Energy and Environmental Design (LEED) best practices (M) based on the method developed by Mendler et al. (2006); and, finally, best practices for sustainable contracts in public administration (PA). For each one of the best practices (and its deployments) it was assigned a letter and a number code. The letters correspond to their origin category (S, B, G, LC, M and PA) and the numbers were

assigned in two ways. When the best practice comes from the survey stage (S and B), the number means the importance ranking order, defined by the experts. Concerning the other best practices, the number corresponded to the ranking order existing in the literature.

4. Results and discussion

This section presents the results for each one of the four steps of the study as well as its consequences and relevant discussions.

4.1. Main building techniques of urban infrastructure designs

After the identification of the building techniques of urban infrastructure designs, the five major design types were established: drainage; water and sewage systems; paved areas; fencings; temporary construction facilities. Fig. 2 brings the relationship between the main building techniques with the urban infrastructure typologies of design.

The most usual building techniques among those designs analyzed were, in descending order of use: cast-in-place reinforced concrete, concrete mixed on site, earthmoving, timber formwork, mortar mixed on site, and massive brick masonry. Considering the design typologies, paved areas have a larger number of associated building techniques, due to the availability of a large variety of materials on the market. With regard to their application in construction stage, only four of the 22 building techniques do not involve preparation or cutting work: laying of crushed stone powder; graded gravel settlement; laying and grouting with sand; con-

| BUILDING TECHNIQUES | URBAN INFRASTRUCTURE DESIGNS | | | | |
|-----------------------------------|------------------------------|----------|-------------|----------------------|--------------------------|
| | Drainage | Fencings | Paved Areas | Temporary facilities | Water and sewage systems |
| Asphalt Cement | | | X | | |
| Basalt element | | | X | | |
| Bituminous concrete | | | X | | |
| Cast-in-place reinforced concrete | X | | X | X | X |
| Concrete mixed on site | X | X | X | | X |
| Container rental | | | | X | |
| Ductile iron element | X | | | | X |
| Earthmoving | X | X | X | | X |
| Fiber cement element | | | | X | |
| Graded gravel settlement | | | X | | |
| Granite element | | | X | | |
| Laying and grouting with sand | | | X | | |
| Laying of crushed stone powder | | | X | | |
| Laying of tactile element | | | X | | |
| Massive brick masonry | X | | | | X |
| Mortar mixed on site | X | | X | | X |
| Paving aggregate mixture | | | X | | |
| Plumbing | X | | | | X |
| Plywood board structure | | | | X | |
| Precast concrete element | X | X | X | | X |
| Timber formwork | X | | X | X | X |
| Wooden fence post | | X | | | |

Source: adapted from TCPO, 2104; ORSE, 2016; SINAPI, 2016

Fig. 2. Relationship between main building techniques with urban infrastructure typologies of design. Source: Adapted from TCPO (2104), ORSE (2016) and SINAPI (2016).

Table 2
Percentage cost of main building techniques adopted.

| Main techniques employed | Urban design typologies | | | |
|-----------------------------------|-------------------------|---------|-------------|--------------------------|
| | Drainage | Fencing | Paved areas | Water and sewage systems |
| Barbed or annealed wire | – | 0.57% | – | – |
| Basalt element | – | – | 4.65% | – |
| Cast-in-place reinforced concrete | – | – | 32.48% | 21.57% |
| Earthmoving | 2.47% | 40.68% | 21.66% | 13.11% |
| Galvanized steel element | – | 5.59% | – | – |
| HDPE plumbing | – | – | – | 10.66% |
| Laying of tactile element | – | – | 2.70% | – |
| Massive brick masonry | 13.57% | – | – | 9.85% |
| Mortar mixed on site | 10.81% | – | – | – |
| Precast concrete element | 56.43% | 49.72% | 5.25% | – |
| Wooden fence post | – | 1.19% | – | – |

tainer rental. The other building techniques involve cutting, preparation work, or both procedures.

4.2. Waste production by construction stages

For the identification of CW production infrastructure constructions, there was the documentary analysis of 14 urban infrastructure projects of different typologies. To identify the CW generation, in case of already executed projects, the actual waste generation data were considered; for those in progress, forecast data of the construction wastes management plans were used.

Analyzing different design types in the 14 projects, 10 of them (71.40%) had the construction of drainage in its scope; six (42.90%) of water and sewage systems; 13 (92.90%) of paved areas; and six (42.90%) of fencing. Table 2 presents as percentage of the total projects, the five most economically relevant building techniques employed, considering the design type and the infrastructure services performed.

Among the adopted techniques, it was found that the earthmoving is economically representative in all design types. The use of precast concrete element proved relevant in both drainage and fencing designs, reaching more than a half of the average cost of the projects. In paved area designs, costs were balanced, being

considered as significant the cost of cast-in-place reinforced concrete.

In temporary facilities of construction sites, there were employed, mainly: construction sidings and sheds, each one with a use percentage of 85.71% (12 projects); stalls for aggregate storage, with 64.29% (nine projects); siding screen, with 35.71% (five projects); and open warehouse, with 14.29% (two projects). In terms of most usual building techniques, it has been identified, mainly: plywood board structure (3348.99 m² in 11 projects); fiber cement roof sheet (688 m² in nine projects); container rental (10 units in five projects); and polyethylene siding screen (1159.20 m in five projects).

To measure the quantities of wastes generation, it was used a standard unit of m³ CW/built m². That allows identifying the proportion of those wastes considering the total area of the project intervention. The CWs were categorized according to CONAMA's Resolution no. 307 of July 5, 2002 (Brazilian Government – Environmental Protection Agency, 2002). Thus, the wastes classified as Class A have the potential for reuse or recycling as aggregate, such as soil, bricks, concrete and mortar. The wastes classified as Class B are recyclables for other applications, such as plastic, wood, and steel. The wastes classified as Class D are hazardous construction wastes, such as paint, solvent, and oil. Table 3

Table 3
CW average volume by the type of the design and by the construction stage.

| CW Class | Generate CW volume (m ³ CW/built m ²) | | | | Construction stage | Potential generators constructive processes |
|---------------------------------|--|---------------|---------------|------------------|--|---|
| | Drainage | Fencing | Paved areas | Water and sewage | | |
| Class A | 0.1705 | 0.2226 | 0.1571 | 0.2341 | Land preparation | Land clearing and stumping |
| | | | | | Pavement construction | Laying of pavement with mortar Basalt board cutting Precast concrete curb cutting Pavement cut with precast concrete block Tactile floor cutting |
| Class B | 0.0123 | 0.0019 | 0.0094 | 0.0203 | Installation of drainage and systems of sewage and water | Trench digging Loan soil backfill Precast concrete channel cutting Execution catch-basin in masonry Ballast execution with concrete mixed on site |
| | | | | | | Installation of drainage and systems of sewage and water |
| Class D | 0.0038 | 0.0006 | 0.0029 | 0.0063 | Pavement construction | Disposal of paints of horizontal road marking and solvents Disposal of contaminated paint material |
| | | | | | Temporary facilities | Disposal of sidings, sheds, stalls and warehouse's benefited woods |
| Total per type of design | 0.1866 | 0.2251 | 0.1694 | 0.2608 | – | – |

Table 4
Design strategies mentioned for reduce CW, according to the experts.

| Design strategies | Resulting importance (%) | Distribution of experts' citations (%) | | | |
|---|--------------------------|--|------------------|---------------------|-----------------------|
| | | Designers | Project managers | Building inspectors | Environmental analyst |
| 1 Full communication between project team and environmental analysts during the design stage | 13.97 | 0.00 | 0.00 | 0.00 | 100.00 |
| 2 Adequate and coordinated detailing of design components | 13.71 | 66.67 | 33.33 | 0.00 | 0.00 |
| 3 Planning for reuse of employed materials | 8.02 | 12.50 | 50.00 | 37.50 | 0.00 |
| 4 Planning of construction wastes management | 7.87 | 50.00 | 33.33 | 16.67 | 0.00 |
| 5 Use of standardized materials and building techniques | 7.41 | 100.00 | 0.00 | 0.00 | 0.00 |
| 6 Employment of rationalized and industrialized materials and building techniques | 7.36 | 58.34 | 33.33 | 8.33 | 0.00 |
| 7 Proper use of the land to reduce earthmoving | 6.35 | 100.00 | 0.00 | 0.00 | 0.00 |
| 8 Correct and precise quantification of materials employed | 5.03 | 0.00 | 100.00 | 0.00 | 0.00 |
| 9 Complete and detailed technical specifications (in both project and product) | 4.57 | 0.00 | 100.00 | 0.00 | 0.00 |
| 10 Adoption of modular systems | 4.42 | 37.50 | 50.00 | 12.50 | 0.00 |
| 11 Use of integrated design techniques (BIM tool) | 3.40 | 100.00 | 0.00 | 0.00 | 0.00 |
| 12 Employment of materials durable and with recognized quality | 3.05 | 25.00 | 50.00 | 25.00 | 0.00 |
| 13 Proper construction site planning | 2.59 | 66.67 | 33.33 | 0.00 | 0.00 |
| 14 Full and proper survey of design demands (Requirements program) | 2.54 | 66.67 | 33.33 | 0.00 | 0.00 |
| 15 Stock control and staging of materials on construction site | 2.54 | 33.34 | 33.33 | 33.33 | 0.00 |
| 16 Preference for transportation of materials in short-range | 2.13 | 100.00 | 0.00 | 0.00 | 0.00 |
| 17 Adoption in paved areas of techniques and materials that allow their adaptation to other area uses | 1.68 | 100.00 | 0.00 | 0.00 | 0.00 |
| 18 Consideration of materials' inherent wastes in design stage | 1.68 | 40.00 | 40.00 | 20.00 | 0.00 |
| 19 Projective prediction for wastewater treatment on construction site planning | 1.68 | 0.00 | 100.00 | 0.00 | 0.00 |

presents the average volumes of CW generated by urban infrastructure design type as well as both by the stages of construction and by the construction processes, possibly responsible for this generation.

There was a total of 0.8419 m³ of CW/built m² in the 14 analyzed projects, out of which 0.7844 m³/m² (93.17%) are class A wastes; 0.0438 m³/m² (5.21%) are class B wastes; and 0.0137 m³/m² (1.62%) are class D wastes. The higher CW total volumes are linked to water and sewage systems projects (30.98%) and fencing (26.74%), which together are responsible for more than a half of the total generated waste (57.72%). Assessing the generated CW by class, the water and sewage systems projects are the largest generators in three classes (29.85% of class A, 46.32% of class B, and 46.35% of class D). For waste of class A, there are the fencing projects in second place, with 28.38%, whereas for class B and class D, drainage projects go in second with 28.08% and 27.74%, respectively.

4.3. Identification of improvement opportunities

This section presents potential improvement opportunities for urban infrastructure designs development, which were identified through the survey with experts. The results obtained are shown in the sequence.

4.3.1. Analysis of question no. 1: design strategies

The first question referred to the identification of design strategies that contribute to reduce the CW generation in urban infrastructure. Table 4 shows the 19 strategies mentioned in descending order of importance as well as the percentage of answers associated with each technical expertise.

Out of the 19 strategies, seven of them (3, 4, 6, 10, 12, 15 and 18) showed a convergence of view between designers, project managers, and building inspectors, reinforcing the idea that certain strategies are more important concerning different backgrounds. And from that survey, there was a relationship between the design stages to verify on what activities the strategies may apply. Table 5

shows these relationships between the strategies identified and the design activities, highlighting the five most important ones.

The design activities with the largest number of related strategies are: establishment of criteria and design standards (activity 2.8); specification of materials (activity 3.5); and definition of construction site planning actions (activity 4.3). Considering the five priority strategies and the activities identified, the activities 2.8, 4.3 and 4.4 are the ones that concentrate the most of them. In addition, on average, six strategies were related to each design activity. The 'use of integrated design techniques' (strategy 11), as it was related to the 14 activities, it was also the most adopted one, followed by 'proper use of the land' (strategy 7), related to 13 activities, and 'full communication between project team and environmental analysts' (strategy 1), related to 11 activities.

4.3.2. Analysis of question no. 2: implementation barriers

The survey on potential barriers to the implementation of the proposed design strategies was important to identify improvement on opportunities, mainly because it is a study applied to the public sector. This is due to the fact that Brazilian public agencies are ruled by specific laws, which can limit or even prevent the use of some approaches. According to Oliveira and Melhado (2002), it is one of the main reasons for the difficulty of adopting innovative methods to manage contracts and projects in the public sphere. Table 6 shows the 12 barriers identified by experts, in descending order of importance.

Based on both the barriers prioritization and the literature review, the gap between design and construction teams is pointed as the predominant factor in the quality decreasing on public constructions. That barrier favors rework and hinders the information feedback process to teams involved in future projects of the same nature (Oliveira and Melhado, 2002). On the other hand, tight deadlines for development of design (barrier no. 5) commonly propitiate the recurrent adoption of inappropriate solutions, which strengthens the improvisation culture during the construction process (4th most important barrier).

Table 5
Relationship between design activities and strategies.

| Design stages | Activity number | Design activity | Design strategies | | | | | | | |
|-------------------------|-----------------|---|-------------------|----|----|----|----|----|----|----|
| 1. Requirements program | 1.1 | Establishment of mandatory requirements and design performance requirements | 14 | - | - | - | - | - | - | - |
| | 1.2 | Definition of construction type, main features and simplified dimension | 1 | 7 | 14 | 17 | - | - | - | - |
| | 1.3 | Identification of utilization requirements (water, sewage, traffic, among others) | 14 | - | - | - | - | - | - | - |
| 2. Feasibility studies | 2.1 | Site selection | 1 | 7 | 14 | - | - | - | - | - |
| | 2.2 | Analysis of enterprise's area of influence | 7 | - | - | - | - | - | - | - |
| | 2.3 | General surveys: planialtimetric, and geological-geotechnical, including soil and groundwater | 7 | 14 | - | - | - | - | - | - |
| | 2.4 | Climatological and Hydrological survey: natural drainage, rainfall system, and rainfall rates | 7 | 14 | - | - | - | - | - | - |
| | 2.5 | Environmental characteristics and vegetal coverage survey | 1 | 7 | 14 | - | - | - | - | - |
| | 2.6 | Concessionaires' data evaluation of the existing networks | 14 | - | - | - | - | - | - | - |
| | 2.7 | Verification of the applied regulation and legal requirements | 1 | 3 | 7 | 14 | - | - | - | - |
| | 2.8 | Establishment of criteria and design standards | 1 | 3 | 5 | 6 | 7 | 10 | 12 | 17 |
| | 2.9 | Analysis of possible constructive solutions | 5 | 6 | 10 | 17 | - | - | - | - |
| | 2.10 | Comparison of available solutions | 5 | 6 | 10 | - | - | - | - | - |
| | 2.11 | Selection of appropriate solution(s) | 5 | 6 | 10 | - | - | - | - | - |
| | 2.12 | Analysis of project technical feasibility | 1 | 7 | 11 | 17 | - | - | - | - |
| 3. Basic design | 3.1 | Definition of the constructive method | 1 | 5 | 6 | 10 | - | - | - | - |
| | 3.2 | Design of the system conception | 1 | 7 | 11 | 12 | 17 | - | - | - |
| | 3.3 | Assessment of the environmental impact considering the chosen mitigation actions | 1 | 4 | 7 | 11 | 12 | 17 | - | - |
| | 3.4 | Dimensioning of constructive solutions | 10 | 11 | - | - | - | - | - | - |
| | 3.5 | Specification of materials | 3 | 5 | 6 | 9 | 10 | 12 | 16 | - |
| | 3.6 | Development of complementary designs | 2 | 11 | - | - | - | - | - | - |
| | 3.7 | Coordination of designs | 2 | 11 | - | - | - | - | - | - |
| | 3.8 | Development of the descriptive memorial and memories of calculation | 8 | 9 | 11 | 18 | - | - | - | - |
| | 3.9 | Establishment of construction's deadlines - preliminary schedule | 11 | - | - | - | - | - | - | - |
| | 3.10 | Quantification of materials, equipment and services | 2 | 8 | 9 | 11 | 18 | - | - | - |
| | 3.11 | Elaboration of the preliminary budget | 8 | 11 | 18 | - | - | - | - | - |
| 4. Executive design | 4.1 | Elaboration of constructive details and designs' interfaces | 2 | 11 | 18 | - | - | - | - | - |
| | 4.2 | Elaboration of final plans | 2 | 11 | - | - | - | - | - | - |
| | 4.3 | Definition of construction site planning actions | 1 | 3 | 4 | 7 | 13 | 15 | 19 | - |
| | 4.4 | Elaboration of construction wastes management plan | 1 | 3 | 4 | 7 | 13 | 19 | - | - |
| | 4.5 | Review and complementation of descriptive memorials and calculation memories | 8 | 9 | 11 | 18 | - | - | - | - |
| | 4.6 | Definition of loans and dumping areas, if necessary | 4 | 16 | 18 | - | - | - | - | - |
| | 4.7 | Elaboration of the final budget | 2 | 8 | 9 | 11 | 18 | - | - | - |

Table 6
Barriers to strategies' implementation, according to the experts.

| Barriers to the strategies' implementation | | Resulting importance (%) | Distribution of experts' citations (%) | | | |
|--|---|--------------------------|--|------------------|---------------------|-----------------------|
| | | | Designers | Project managers | Building inspectors | Environmental analyst |
| 1 | Lack of communication between designers and construction professionals | 18.41 | 0.00 | 100.00 | 0.00 | 0.00 |
| 2 | Indifference to environmental issues in both design and construction stages | 14.96 | 50.00 | 0.00 | 50.00 | 0.00 |
| 3 | Cultural resistance to new building techniques and new design strategies | 12.43 | 75.00 | 25.00 | 0.00 | 0.00 |
| 4 | Culture of construction improvisation | 11.28 | 50.00 | 0.00 | 50.00 | 0.00 |
| 5 | Limited time to development of designs | 10.47 | 57.14 | 28.57 | 14.29 | 0.00 |
| 6 | Lack of manpower training for construction stage at all levels | 6.50 | 75.00 | 25.00 | 0.00 | 0.00 |
| 7 | Failure of communication between design team professionals | 6.16 | 50.00 | 0.00 | 0.00 | 50.00 |
| 8 | Lack of long-term planning | 5.70 | 100.00 | 0.00 | 0.00 | 0.00 |
| 9 | Difficulty in proving the recycled or waste-based materials' quality | 5.18 | 0.00 | 0.00 | 100.00 | 0.00 |
| 10 | High cost of industrialized and innovative building techniques | 3.11 | 50.00 | 37.50 | 12.50 | 0.00 |
| 11 | Manpower variability in public constructions | 2.93 | 0.00 | 100.00 | 0.00 | 0.00 |
| 12 | Designers' lack training | 2.88 | 50.00 | 37.50 | 12.50 | 0.00 |

4.3.3. Analysis of question no. 3: reasons for CW generation during construction stage

The main purpose of question no. 3 was to identify the causes of waste generation during the construction stage, and how they could be related to the design process. Table 7 presents the 15 reasons, in descending order of importance, pointed out by experts to CW generation, identifying 12 reasons related to the design stage.

From that survey, we identified that some reasons (1, 5, 8, 11 and 15) are attached directly to either designers or builders' behavior, and they are not necessarily linked to the design decision-making process. Also, there were identified interrelationships

among the cited reasons, as in the case of the reason 15: improper storage of raw materials. The CW generation associated to improper storage can be caused by lack of construction control as well as by the superficial planning of the construction site (reason no. 7).

Based on the reason 'Lack of construction site planning', a further investigation was carried out to identify a possible relationship between the quality of temporary facilities and the CW amount in the studied constructions (step 2 of the paper). The seven constructions with a higher volume of generated CW were analyzed by a four-point rating scale, from 1 to 4. The score 1

Table 7
Reasons to CW generation in the construction stage.

| Reasons for CW generation during construction stage | | Resulting importance (%) | Relationship with the design stage |
|---|--|--------------------------|------------------------------------|
| 1 | Indifference with environmental impacts generated by the activity | 12.68 | X |
| 2 | Material waste due to lack of designs coordination | 10.07 | X |
| 3 | Adoption of systems that intrinsically generate more CW | 8.93 | X |
| 4 | Elaboration of inappropriate construction waste management plan, without effective actions | 8.44 | X |
| 5 | Material wastes and rework associated with unskilled manpower | 8.27 | |
| 6 | Inadequate planning of construction stage | 7.78 | |
| 7 | Lack of construction site planning | 7.29 | X |
| 8 | Lack of control in the use of non-industrialized techniques | 6.70 | X |
| 9 | Unclear or non-existent detailing of design for construction stage | 6.04 | X |
| 10 | Lack of design modularisation | 5.23 | X |
| 11 | Lack of control and supervision of the construction | 4.90 | |
| 12 | Lack of production rationalization | 4.79 | X |
| 13 | Projective lack of prediction of the materials reuse | 3.70 | X |
| 14 | Lack of appropriate technical specification for activity performing | 3.38 | X |
| 15 | Improper storage of raw materials | 1.80 | X |

Table 8
Most cited building techniques.

| Building techniques | Number of citations by design typology | | | | | Total of citations |
|-----------------------------------|--|---------|-------------|----------------------|------------------|--------------------|
| | Drainage | Fencing | Paved areas | Temporary facilities | Water and sewage | |
| Asphalt cement | – | – | 10 | – | – | 10 |
| Basalt element | – | – | 16 | – | – | 16 |
| Bituminous concrete | – | – | 6 | – | – | 6 |
| Cast-in-place reinforced concrete | 3 | – | 5 | 3 | 3 | 14 |
| Concrete mixed on site | 3 | 5 | 9 | – | 6 | 23 |
| Container rental | – | – | – | 17 | – | 17 |
| Ductile iron element | 4 | – | – | – | 5 | 9 |
| Earthmoving | 18 | 10 | 13 | – | 18 | 59 |
| Fiber cement element | – | – | – | 7 | – | 7 |
| Graded gravel settlement | – | – | 13 | – | – | 13 |
| Granite element | – | – | 7 | – | – | 7 |
| Laying and grouting with sand | – | – | 14 | – | – | 14 |
| Laying of crushed stone powder | – | – | 14 | – | – | 14 |
| Laying of tactile element | – | – | 10 | – | – | 10 |
| Massive brick masonry | 9 | – | – | – | 7 | 16 |
| Mortar mixed on site | 8 | – | 8 | – | 8 | 24 |
| Paving aggregate mixture | – | – | 8 | – | – | 8 |
| PVC plumbing | 13 | – | – | – | 14 | 27 |
| Plywood board structure | – | – | – | 18 | – | 18 |
| Precast concrete element | 14 | 17 | 16 | – | 15 | 62 |
| Timber formwork | 2 | – | 4 | 10 | 2 | 18 |
| Wooden fence post | – | 9 | – | – | – | 9 |

referred to the construction sites without planning, the score 2 referred to the construction sites with poor planning, the score 3 referred to the construction sites with good planning, and the score 4 referred to the construction sites with excellent planning.

Thus, it was confirmed the direct relationship between the quality of the planned construction site and the amount of construction waste. As a result, the four constructions with the highest CW generation had the construction site classified as poor (score 2); the intermediate two constructions were classified as good (score 3); and one construction, which generates less CW was considered excellent (score 4). In this way, it was understood that the temporary facilities planning may be relevant to reduce the waste generation related to the projects.

4.3.4. Analysis of question no. 4: most usually employed building techniques

Question 4 sought to identify the main construction practices related to typologies of urban infrastructure designs studied. The interviewed experts were asked to emphasize the most commonly employed building techniques to each design type from a given list, which was originated from the contents of Fig. 2. Table 8 shows the most building techniques identified by the experts, by

the design typology, and by the number of citations. The most cited techniques are highlighted in the table.

From the experts' point of view, it was made a comparison between the most cited building techniques and those used in the projects analyzed, in Section 4.2. All the techniques cited by experts were employed on drainage projects; in other project types, the use of these techniques achieved approximately 80% for paved areas, and around 60% for water and sewage systems, fencing and temporary facilities.

4.3.5. Analysis of question no. 5: highest and lowest CW generation by building techniques

In question 5, the experts pointed out both the highest and the lowest CW generation by building techniques, according to each design type. In many cases, the same technique was considered as higher and lower CW generator, simultaneously, which means conflict between points of view, especially among designers and project managers. From Figs. 3–7 show charts of the building techniques considered the highest and the lowest waste generators by the experts, for each design type.

Crossing information of Figs. 3–7 with the ones of question no. 4 allowed verifying the relationships between the five main types of

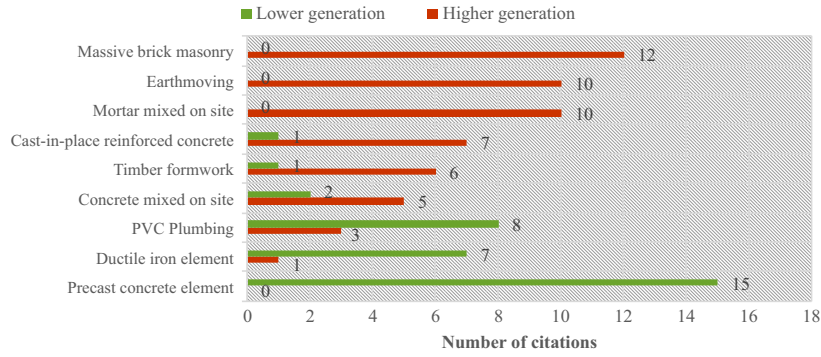


Fig. 3. Lowest and highest CW generator techniques in water and sewage systems designs.

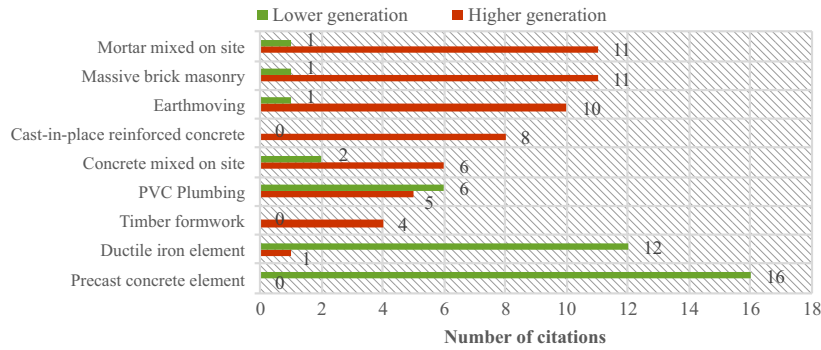


Fig. 4. Lowest and highest CW generator techniques in drainage designs.

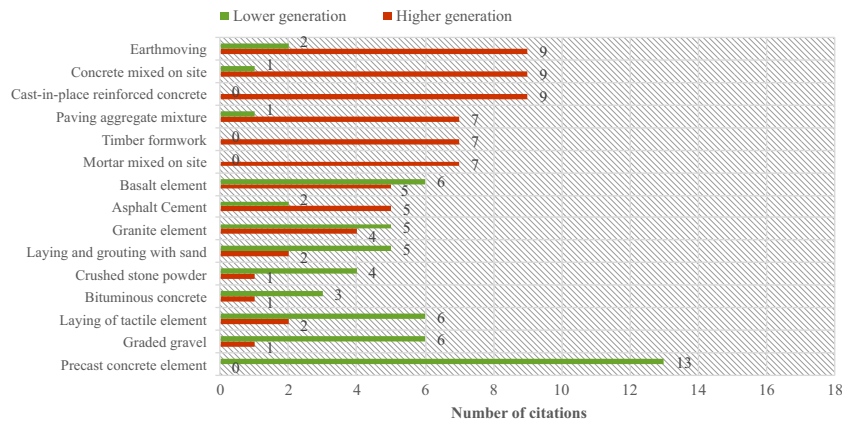


Fig. 5. Lowest and highest CW generator techniques in paved areas designs.

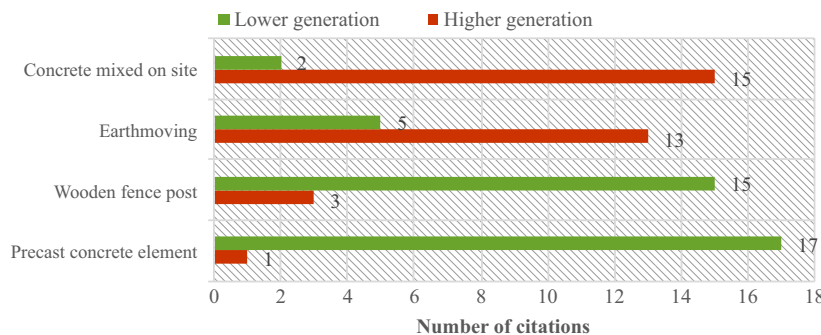


Fig. 6. Lowest and highest CW generator techniques in fencing designs.

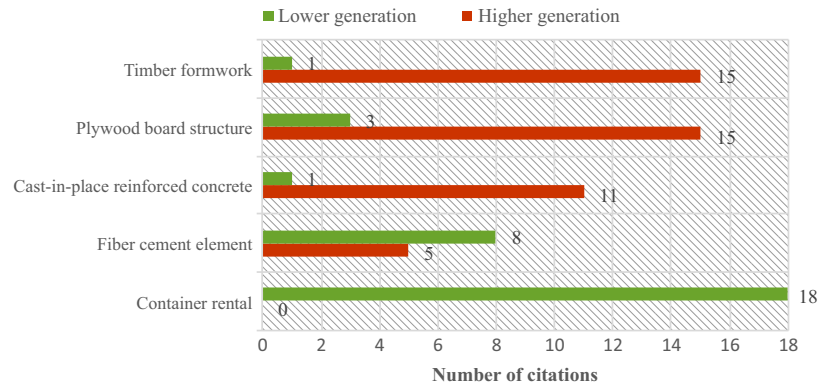


Fig. 7. Lowest and highest CW generator techniques in temporary facilities designs.

the usually employed building techniques and the largest CW generators. It was found that: for drainage, and water and sewage systems projects, three of the main building techniques adopted (earthmoving, mortar and masonry) were also the highest waste generators; precast concrete element technique has the lower CW generation; and the PVC plumbing had conflict classification.

In paved area projects, earthmoving technique was the largest CW generator; precast concrete element, laying and grouting with sand and laying of crushed powder were the ones with lower CW generation; and basalt element technique had conflict classification. In fencing, two of the most widely used techniques, earthmoving and concrete mixed on site, were indicated as the highest generators as well as precast concrete element and wooden fence post were the lowest CW generators. Finally, in the case of temporary facilities, the three most used techniques were among the largest CW makers (plywood board structure, timber formwork and cast-in-place reinforced concrete) and two techniques were considered the lowest producers (container rental and fiber cement element).

It was observed a conflict classification on the following building techniques (and its typologies): PVC plumbing in drainage projects; and basalt and granite element in paved area projects. A possible explanation of that dichotomy might be that experts' assessment of the degree of waste generation based on their professional observations and, in the case of cited techniques, the cutting is not solely related to the material but mainly to the design modularization adopted.

In addition, considering the 14 public projects analyzed in this study, it appears that the higher CW generator types were water and sewage systems. The reason for that may be related to the fact that this typology employed a large number of techniques, which are considered the largest waste generators through experts, namely: earthmoving; mortar; and masonry. Considering those results, and associating with the guidelines identified in the literature, in the next section, we identified the best practices for reduction the construction waste in the design stage.

4.4. Best practices for reduction of CW in the design stage

The best practices identified in this study have two main themes: design, which deals with design stages; and management, which refers to conduction of the design process. Each one of the theme has four groups, totaling 33 best practices (including ten deployments). Table 9 shows the best practice list.

The best practices resulting from the strategies nos. 1, 3, 5, 6, 18, and M4 were divided into ten possible ways to achieve their related objectives. In some cases, the deployments represent usually construction practices, such as G8, referring to the best prac-

tice of material reuse planning. G8 suggests the use of cutting materials as aggregates, which it is a practice used on paved area, and it is standardized by NBR 15.116/2004 (ABNT, 2004). Moreover, the Brazilian Federal Government's Normative Instruction No. 01, which refers to the sustainability criteria in public administration, obliges the use of aggregate recycled on public projects, by building contractors, when it is possible (Brasil, 2010).

Best practice M5 and deployment G10 highlighted that not only the amount of waste requires attention because of its environmental impacts, but also about the hazard of the material (Yang et al., 2017). When a rental structure is not used in temporary facilities, they are made up of plywood boards or other types of treated wood, which are classified as class D waste (hazardous). Based on the diagnosis of the constructions analyzed in this study, it was perceived an inadequate control of the demobilization construction waste, which increases the risk of irregular disposal.

The best practice M2 highlights the approach through the life cycle cost analysis (LCCA) of the products for a full and proper economic evaluation of design choices. According to Mendler et al. (2006), the life cycle involves all stages of a product on the environment, from its raw materials extraction to its final disposal. On LCCA it is considered the costs over the whole life of the product (acquisition, use, operation, maintenance and disposal), performing a balance between economic and environmental impacts to guide the decision for the best value. This analysis becomes relevant to justify the higher cost of less environmentally impactful acquisition of products considering lower cost options in the market, especially in specifications of the public projects.

The best Practice S7 emphasizes the importance of a proper assessment of land to minimize earthmoving. In that sense, it was observed that, according to Table 3, the item earthmoving was presented as economically relevant for all project types analyzed. And, as seen in their waste generation diagnosis, most of the CW was originated from this building technique, which makes it a very expensive and also a large waste generator. This finding is consistent with those by Marrero et al. (2017) who found that large volumes of wastes generated in urbanization works are due to earthmoving and tree felling.

The group 'design integration', which is a relevant issue both in design and construction management, is discussed here under different perspectives once the acquisition of specialized software for this purpose is not always feasible. In the case of software availability, it appears that the use of BIM technology can contribute to the achievement of 10 best practices: S1, S2, S3, S8, S9, S10, S13, S18, G1 and M4. However, if the use this technology is not possible, integration can be inserted into the design stage through the use of methods to facilitate communication between the design team as well as the information flow. Thus, it is understood

Table 9
Best practices to reduce CW.

| Theme | | Reference source |
|--|---|--|
| <i>Group</i> | | |
| Design | | |
| <i>Design concept</i> | | |
| Code | Best practices and deployments | |
| S7 | Proper use of the land to reduce earthmoving | Survey; Marrero et al. (2017) |
| S17 | Adoption in paved areas of techniques and materials that allow their adaptation to other area uses | Survey |
| G4 | Design solutions less complex in order to reduce failures in construction | Udawatta et al. (2015) |
| LC1 | Full knowledge of project requirements focused on reducing of CW generation as generation of value | Marhani et al. (2012) |
| M1 | Establishment of CW generation minimization as a design strategy | Mendler et al. (2006) |
| <i>Design integration</i> | | |
| Code | Best practices and deployments | |
| S1 | Full communication between project team and environmental analysts during the design stage | Survey |
| G5 | Establishment of daily routine of meetings between design's teams | Udawatta et al. (2015) |
| M4 | Use approaches of the integrated and collaborative design process | Mendler et al. (2006) |
| S11 | Use of integrated design techniques (BIM tool) | Survey |
| <i>Design optimization</i> | | |
| Code | Best practices and deployments | |
| S2 | Adequate and coordinated detailing of design components | Survey |
| S8 | Correct and precise quantification of materials employed | Survey |
| S9 | Complete and detailed technical specifications (in both project and product) | Survey |
| S14 | Full and proper survey of design demands (Requirements program) | Survey |
| S18 | Consideration of materials' inherent wastes in design stage | Survey |
| G2 | Dissemination of wastes generation indices to professionals to support decision-making processes | Udawatta et al. (2015) |
| G6 | Considering Life Cycle Assessment (LCA) as a decision-making tool | Mendler et al. (2006) and Udawatta et al. (2015) |
| M2 | Including the product's Life Cycle Cost Analysis (LCCA) on design scope | Mendler et al. (2006) |
| <i>Materials and building techniques</i> | | |
| Code | Best practices and deployments | |
| S5 | Use of standardized materials and building techniques | Survey; Esa et al. (2017) |
| PA1 | Employment of reused, recycled and other materials with reduced maintenance | Brasil (2010) |
| M5 | Choosing environmentally less impacting building techniques to prevent the use of toxic materials | Mendler et al. (2006) and Begum et al. (2007) |
| S6 | Employment of rationalized and industrialized materials and building techniques | Survey |
| B2 | Investments in innovative processes and techniques to achieve less generation of CW | Survey; Udawatta et al. (2015), Wang et al. (2015) and Esa et al. (2017) |
| G7 | Use of metal formwork instead of timber formwork to maximize the reuse possibilities | Jaillon et al. (2009) and Wang et al. (2014) |
| G9 | Priority on the use of dry building techniques | Wang et al. (2014) |
| G10 | Priority on the use of rental ready structures in temporary construction facilities | Wang et al. (2014) |
| S10 | Adoption of modular systems | Survey; Esa et al. (2017) |
| S12 | Employment of materials durable and with recognized quality | Survey |
| S16 | Preference for transportation of materials in short-range | Survey |
| G11 | Avoid the use of on site execution building techniques (mortar, concrete, and masonry) with the preferential employ of precast technologies | Tam et al. (2007), Wang et al. (2014) and Yang et al. (2017) |
| Management | | |
| <i>Construction waste management</i> | | |
| Code | Best practices and deployments | |
| S3 | Planning for reuse of employed materials | Survey; Marrero et al. (2017) |
| G8 | Projective prediction for the use of recycled materials as aggregates | Wang et al. (2014), Brasil (2010) and Marrero et al. (2017) |
| S4 | Planning of construction wastes management | Survey |
| S19 | Projective prediction for wastewater treatment on construction site planning | Survey |

(continued on next page)

Table 9 (continued)

| Theme | Reference source |
|---|--|
| G1 Planning of construction activities, focusing on potential CW generators' stages | Poon et al. (2004) and Solís-Guzmán et al. (2009) |
| <i>Construction site management</i> | |
| Code Best practices and deployments | |
| S13 Proper construction site planning | Survey; Ekanayake and Ofori (2004), Saez et al. (2013) |
| S15 Stock control and staging of materials on construction site | Survey |
| <i>Design process management</i> | |
| Code Best practices and deployments | |
| G3 Appropriate documentary record of decisions and design criteria | Udawatta et al. (2015) |
| LC2 Prioritization of process transparency during design stages | Marhani et al. (2012) |
| LC3 Data feedback to design team to prevent changes of design during construction stage | Marhani et al. (2012) |
| LC4 Use of schedule monitoring methods | Ghosh et al. (2014) |
| M3 Establishment of design performance goals and related measurement standards | Mendler et al. (2006) |
| <i>Design team</i> | |
| Code Best practices and deployments | |
| B1 Investments on design team's training to promote the environmental awareness in design decision-making | Survey; Bakshan et al. (2017) |
| B3 Investments on design team's qualification regarding the use of innovative processes and techniques | Survey; Ekanayake and Ofori (2004) |

that the design process management best practices group expresses alternative ways to obtain the necessary integration without specialized software but through collaborative design process approach.

Thereby, the best practice list can contribute to the design process by the intervention on both different design and planning stages. We also suggested that the best practices and their deployments could be used as control and evaluation instruments to support the decision-making process, as a checklist (Appendix A and Appendix B). That checklist consists of a helpful tool to urban infrastructure designs development, focusing on the reduction of CW.

5. Conclusions

This study was developed from the need to reduce environmental and economic impacts caused by material waste in urban infrastructure projects, aiming the identification of best practices to support the design stage. To achieve this goal were used as methodological instruments: literature review; document analysis; and application of qualitative and quantitative survey with experts. After analyzing the data, it was possible to make some considerations.

One of the main contributions of this study was the identification of the relationships between building techniques employed in urban infrastructure projects in Brazil, and design typologies. Those interactions were the basis for understanding waste generation impacts, and for highlighting the main construction practices used in urban infrastructure projects.

In the step of documentary analysis of public urban infrastructure projects (step 2), there was the waste generation diagnosis, which identified the largest CW generators according to both used building techniques and employed design typologies. Thus, based on the different types of material wastes observed, design choices factors were associated with them, e.g., earthmoving poorly planned; inadequate design modularization; cast-in-place building techniques specifications; and temporary facilities structured with both toxic and few recycled materials. We identified that the earthmoving building technique has economic relevance in all design

types. And it was considered, also, the main responsible for CW generation of the projects.

The third step of the study identified, from the expert's opinions: (i) design strategies to reduce CW generation; (ii) barriers to implementation of strategies; (iii) causes of waste generation in construction stage; and (iv) the highest and lowest waste generators, in most used building techniques, by design type. Analyzing the causes of waste generation on construction stage, we found that they were not only linked to decisions of design, but also to the behavioral component of professionals, which reinforces the need for best practices focused on the awareness of the design team. At that step, it was still possible to conclude about the importance of the construction site designs regarding the proper waste management through the verification of the direct relation between the quality of the construction site planning and the amount of generated CW in the analyzed constructions.

Finally, at the last step of the study, it resulted in a list of 33 best practices, with ten deployments, applicable to design stage and project management, because we understood that both aspects are fundamental to reduce the generation of CW. On the other hand, considering specific characteristics of the public projects, the importance of the principle of economy, expressed in the best practices, has been stressed through the LCCA approach. This approach can be critical to the achievement of more sustainable contracts in public administration, supported by both Brazilian A3P Agenda (Environmental Agenda for Public Sector) thematic axes and Normative Instruction No. 1. The checklist generated from the best practices makes up an important tool for supporting the design decision-making, complementing recommendations made by Mendler et al. (2006).

Therefore, we conclude that the CW generation in urban infrastructure projects has a complex assessment since it is influenced by several factors, from different sources. However, it is considered possible to reduce the waste generation in constructive activity with the appropriate combination of both design choices and management based on the best practices identified, aiming projects with less environmental impact.

Despite the checklist tool generated, we understood that this research has limitations. Thus, as a suggestion for future studies,

we draw attention to the need for the best practice application, as well of a method for their application, considering its relevance in the decision-making process. We also suggest the investigation of both the application of best practices from the Life Cycle Assessment (LCA) approach, as well as the generation of performance indicators applied to the design stage, to promote more sustainable projects.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.wasman.2017.05.025>.

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