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METHOD TO ALLOCATE COVID-19 PREVENTIVE MEANS OF CONSTRUCTION WORKS BASED ON EXPERT PRIORITIZATION

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ABSTRACT

COVID-19 has severely impacted construction projects, not only by contagions and imposed restrictions but also by dynamically changing supply, work, and labor conditions. Management teams have had to adapt to these dynamically constrained conditions, mostly reacting through trial and error. Since decisions regarding planning, resource, and preventive means allocation must consider multiple internal and external conditions such as restrictions, schedule impacts, risks, and costs; this study proposes a method to evaluate the compared criticality of multiple construction work items and select sets of recommended preventive and reactive means accordingly. A criticality assessment tool was developed in collaboration with 11 academic and industry experts using the Analytic Hierarchy Process, which allowed to weight the compared impact of nine criticality criteria. The empirical application in nine work items from three Chilean construction projects allowed to determine four ranges of critically, where expert' proposed sets of measures were recommended. The instrument allows assessing the items using a five-level evaluation scale in nine criteria to determine compared criticality, assign them to one of four criticality ranges and obtain a set of recommended actions.

KEYWORDS

COVID-19, safety, health, action research, construction work prioritization

INTRODUCTION

The construction industry represents approximately 6% of the world's Gross Domestic Product (GDP) (Kenny, 2007) and employs approximately 7.7% of its population (International Labour Organization, 2021). Its main activity consists of project development and infrastructure delivery for residential, industry, and service use. Project execution is highly complex since it involves the collaboration of multiple stakeholders to carry out resource and labor-intensive tasks, which constitute highly interrelated

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activity programs that extend over several months or years (Brissi & Debs, 2019). Also, researchers have long studied how uncertainty and variability negatively impact the dynamicity of construction and induce a tendency for scope, budget, and schedule deviations if not properly controlled (Gómez-Cabrera et al., 2020; Grau et al., 2019; Przywara & Rak, 2021). Under the rapidly changing conditions induced by the COVID-19 pandemic, uncertainty and variability increased considerably, significantly impacting project development and infrastructure delivery (Araya, 2021).

The COVID-19 pandemic has severely impacted the construction industry, and its recovery is key to economic activity and employment creation (de Henau & Himmelweit, 2021; Denny-smith et al., 2021). Many construction companies have experienced severe limitations in their production, planning and control capabilities (Ling et al., 2021) due to supply-chain outages, labor and resource limitations, protocols and restrictions imposed by authorities, among others (Kim et al., 2021). Moreover, the lack of existing protocols for uncontrollable events such as a pandemic and lack of previous experience since a similar event has not occurred globally since the early stages of the 20th-century forces management and execution teams to adapt their strategies through trial and error. Therefore, companies and particularly project teams are being forced to react to impacts after the fact or allocate preventive measures based on their best assessment of current and expected conditions (Jeon et al., 2022).

The sanitary measures established because of the pandemic have affected construction work planning, execution, and control (Parameswaran & Ranadewa, 2021). Traceability requirements make it necessary to know the interaction and contact between crews and the risk associated with the site where these activities occur (Assaad & El-adaway, 2021). In addition, capacity restrictions and personal protection measures vary according to the type of work to be performed, the conditions, and the context in which the work is carried out (Simpeh & Amoah, 2021). Moreover, the effectiveness of measures such as the modification of processes, incorporation of technologies, changes in construction methods or industrialization (Brissi & Debs, 2019; Leontie et al., 2022) depends on the type of work item in which these measures are implemented, the conditions of the worksite, and current risks according to the foreseeable tendency of the contagion rate (Gan & Koh, 2021; Yang et al., 2021).

The need to adopt new sanitary protocols combined with production method changes presents an opportunity to do it in a safer, more productive, and sustainable approach (Assaad & El-adaway, 2021; Verán-Leigh & Brioso, 2021). This can be achieved by integrating infection prevention protocols with production management protocols that incorporate available technologies and methods to implement industrialized, more efficient, and sustainable construction processes that allow safer and more productive construction (Al-Mhdawi et al., 2021; Brissi & Debs, 2019). Nevertheless, since implementing such protocols, managerial and production changes can be costly and resource-intensive, project managers and safety professionals need to prioritize preventive, proactive, and reactive actions (Hallowell et al., 2013).

It is a complex endeavor to prioritize how to secure productivity and schedule viability while lowering the expected risks of contagion or other impacts on the project and its team (Yang et al., 2021). Furthermore, since conditions vary rapidly and often, current protocols and implemented actions can rapidly cease to suit the project’s best interest or cause unexpected side effects (Chih et al., 2022; Gan & Koh, 2021). Selecting a combination of these protocols and actions presents three alternatives: Implementing a minimum required set of preventive measures and accepting a certain level of risk;

oversizing planned preventive measures and accepting greater costs, resources, and effort involved; or allocating a specialized set of measures to different project areas based of risks' probabilities and expected impacts (Assaad & El-adaway, 2021). The latter alternative would require project teams to be able to react in advance to changes through a systematized method of evaluation and prioritization.

Decision-making under these circumstances requires systematically combining planning and control, workforce monitoring, and context data to ensure the most efficient allocation of measures (Amoah & Simpeh, 2021; Kim et al., 2021). Hence, the current situation forces the adoption of information technology (IT) to a greater extent, paving the way for improvements in the integration of IT with project planning and control, resulting in new workplace health and safety protocols adapted to the pandemic context (Ebekozien & Aigbavboa, 2021). Suppose available technology, protocols and information use are well integrated. In that case, they can allow to carry out prioritization of needs and available options periodically and in advance, based on risks and potential benefits.

Also, given that the exposure and risk of infection, as well as the loss of productivity and impact on the site, differ according to the type of work item affected, these decision-making systems must consider the type of work and conditions involved in different construction tasks and work items (Gan & Koh, 2021), establishing alternative batteries of measures that best suit each context, risk relevance, and work item assessed (Simpeh & Amoah, 2021). Therefore, this research aims to design a method for evaluating and prioritizing work items at the construction site. In addition, the method will allow a selection of IT-supported alternatives, which can be implemented to reduce the risk of contagion and prevent negative impacts on performance.

RESEARCH METHOD

The research methodology was conducted through action research to secure the study's goals through three main stages: (1) Design of a work item evaluation instrument based on a risk and criticality assessment; (2) applying evaluation instrument in a set of work items from 3 projects to identify criticality cohorts; and (3) proposal of a set of IT-supported actions for each type of work item.

STAGE 1: DESIGN OF THE EVALUATION INSTRUMENT

Three workshops (WS) of 2.5 hours each were carried out to design the evaluation instrument. The participants were 11 people: two were from the research team; two from a Lean project management consulting firm; and seven construction professionals from three large construction companies based in Chile. The consultants were civil engineers with more than 10 years of experience in the application of Lean in construction companies. The seven professionals were civil engineers or construction engineers with more than 10 years of experience, project managers and production managers. Table 1 describes the objective, activities, and deliverable for each workshop.

During the first WS, a set of 19 possible criteria was proposed by the participants and refined until obtaining nine assessment criteria. This refinement consists of grouping similar sets of criteria and creating a more specific description of that set to conform to a new criterion and, thus, reducing the number of areas from 19 to 12. Then, the participants were asked to agree on rating the easiness of evaluation, relevance to assessing criticality, and ability to differentiate items objectively. That assessment concluded with selecting nine relevant, easy to rate, differentiating criteria.

Each participant was asked to use an Analytic Hierarchy Process (AHP) rubric through an Excel template for multiple participants to assess the compared relevance of each criterion against the remaining eight (Klaus, 2013). The AHP is a decision-aiding that aims at quantifying relative priorities for a given set of alternatives on a ration scale, based on the judgement of the decisions-maker, and stresses the importance of the intuitive judgements of a decision-maker as well as the consistency of the comparison of alternatives in the decision-making progress (Can Ylldlrlm et al., 2021). The results were consolidated in WS 2° to create a judgment matrix, and the calculation of the consistency ratio allowed to iterate in the workshop until each individual and the conjoint judgment matrix obtained a consistency equal to or greater than 10%, who it is a typical value in the AHP method (Klaus, 2013). The resulting eigenvector of the judgment matrix represented the relative weight of each criterion within the instrument.

The definition of rating levels for each criterion was carried out in WS 3°. A standard five-level Likert Scale was selected, and each level was assigned a rate in a Fibonacci ladder to differentiate the responses significantly (Can Ylldlrlm et al., 2021). Hence, the resulting levels were very low – 1, low – 3, medium – 5, high – 8, and very high – 13. The participants were asked to propose objective attributes to define the level that better represented a given work item's criticality in each criterion. For example, the participants agreed on five ranges to establish the criticality level of the average crew size. Finally, After the three WS, the instrument was presented to the participants, and a detailed explanation was carried out, enabling them to apply the evaluation instrument in their construction projects.

Table 1. Activities and deliverables from stage 1 workshops

WS	Objective	Activities	Deliverable
1	Identify a set of factors required for the evaluation of work items.	Brainstorming factors for assessing the relevance of a work item Qualitative analysis of factors according to the value of the work item and the ease of evaluation	List of factors
2	Establish a prioritization of the evaluation factor using AHP	Presentation of factors considered in WS1 Preparation of individual judgment matrix and calculation of consistency coefficient. Elaboration of judgment matrix using the median Calculation of weights per factor.	Weights of factors
3	Create a rating rubric for each evaluation factor	Presentation of factor weights in WS2 Definition of rating levels Description of the levels for each factor	Rubric of factors

STAGE 2: EVALUATION OF WORK ITEMS IN CONSTRUCTION PROJECTS

Three construction companies evaluated the criticality of their work items using the instrument created in the previous stage. A total of nine work items from high-rise building projects were evaluated, all of which belonged to the framing construction phase of the projects. After gathering the evaluation results, two meetings were carried out to obtain the results for each work item and make final adjustments to the instrument. The first meeting focused on describing how each team evaluated their work items and aligned criteria, after which a set of recommendations was established to ensure a standardized assessment. The second meeting focused on resolving concerns and capturing proposed adjustments to the evaluation scale, such as refining objective quantitative ranges required for each scale-level in each criterion. The second meeting concluded with a final update of the work items evaluation. Table 2 shows the work items evaluated by each company.

Once the Global Evaluation (GE) index of criticality was obtained for the nine work items, two meetings were held to propose and validate the set of criticality ranges which would be assigned different batteries of measures and actions. These ranges were based on explicit cohorts observed after the evaluation and sensitivity analyses of the changes in the GE caused by changes in the level assigned to each criterion. It was decided that the lowest range of the GE would represent work items in which the vast majority of the criteria was assigned a level equal or lower than medium, hence, a GE≤5.0. Similarly, the highest range, i.e., the most critical, would require that the vast majority of the criteria was assigned a level equal or greater than high, hence, obtaining a GE≥8.0. Finally, the work items with a GE between 5.0 and 8.0 were assessed in detail to determine if additional divisions were needed. After the close assessment, the participants detected that an increase from "medium – 5" to "high – 8" criticality in the three most relevant criteria should require a change in the recommended batterie, which produced a third division that created four final ranges of criticality.

Table 2. Work items evaluated per company

Company	Work items	ID
1	Preparation and placement of foundation reinforcement	1.1
	Installation of basement wall formwork	1.2
	Installation of tower reinforcement	1.3
2	Anchoring of foundation piles	2.1
	Installation of basement wall formwork	2.2
	Installation of basement wall reinforcement	2.3
3	Installation of basement wall reinforcement	3.1
	Excavation of foundation piles	3.2
	Concreting of basement wall	3.3

STAGE 3: PROPOSAL OF A SET OF PREVENTIVE MEASURES

In stage 3, two workshops were held with all the participants of the stage 1 workshops. The first workshop consisted of teaching different technologies and methods to monitor and control people's behavior to mitigate the probability of COVID-19 transmission. Some of the technologies presented were capacity control of work areas, triage survey, distance detection bracelet, cameras for computer vision, video analytics, and ex-situ construction, among others. Also, methods such as the use of the Last Planner® System of production control, location-based planning, Building Information Modelling (BIM), and rule-based automated crew allocation protocols were discussed, introducing the general concepts within each of them. At the end of the workshop, construction professionals shared experiences of effectiveness and possible limitations of the different technologies and methods mentioned.

The second workshop consisted of using the four ranges of criticality obtained in state 2 to differentiate the nine items evaluated and new theoretical work items, to brainstorm, refine and validate a recommended batterie for each of them. The workshop discussed the particularities of each construction site to understand why two similar items had different levels of overall criticality in two different projects and the variance within available resources, capacity, and conditions of each project to determine general case scenarios. Finally, technologies and methods presented in WS 1° of the stage and new ones proposed by the participants were allocated to each criticality range to determine the recommended measures in each batterie.

RESULT AND DISCUSSION

EVALUATION INSTRUMENT

Table 3 describes the nine factors considered critical for evaluating a work item in a construction project and the weight assigned to each factor, obtained from the final judgment matrix. The final inconsistency ratio was 9%, hence, the eigenvector was considered representative of the relative importance of each criterion within the instrument.

Table 3. Description and weight of each criterion in the instrument

Factor	Description	Weight
The item is part of the critical path.	The item’s related schedule activities are part of the project's critical path.	21.30%
Risk personnel within the work item’s crew	Number of unvaccinated, elderly, and base disease staff within the assigned crews	16.80%
City’s expected pandemic phase	Expected phase in a 4-week horizon, on a five-level scale, according to authority-imposed restrictions	15.10%
Average possible social distance in the work area	The health authority defines the maximum capacity of a work area depending on the status of the pandemic.	11.50%
Minimum guaranteed physical distance	Average distance required to execute the tasks required to complete the work item	9.70%
Level and type of ventilation of the area	Type of ventilation of the location where the work will be carried out (open, closed, mixed)	9.00%
Relative cost of the item in budget	Work item unit price per quantity of work, multiplied by the planned work quantity, as a percent of the budget.	6.80%
Necessary specialization in the work item	Level of specialization required to perform the work item (complexity)	6.00%
Number of workers in average crew	Average number of workers per crew needed to carry out the tasks from the work item	3.80%

The participation of the work item’s related activities in the critical path, number of personnel at risk within the crew and expected phase of the pandemic in the next four weeks, based on a five-level scale, account for approximately 53% of the assessed criticality. This allowed to significantly represent the potential impacts of the risk of contagions over the construction site’s personnel and the project’s goals. Also, the average possible social distancing at the area where the work item will be carried out, the minimum guaranteed distance required to carry out the work item’s tasks and the level and type of ventilation available, which add to approximately 30% of the criticality, represent the capacity to prevent contagions while executing the work item. Finally, almost 20% is explained by the complexity of the work item, represented by its cost, required specialization and number of workers involved in its activities.

The criticality of each work item's criterion is represented by a non-linear five-level scale based on a Fibonacci sequence (1, 3, 5, 8 and 13), to help differentiate criticality levels. Specific measurable factors, which are presented in Figure 1, were assigned to each level in each criterion to facilitate the criticality assessment. These factors were based on the most relevant attributes needed by the academic and industry experts to assess the work items in each criterion and agreed upon at the end of stage 2. It must be noticed that these factors came from the use of the instrument within the Chilean context, they were generalized so that the same instrument could be applied internationally. Finally, as Figure 2 presents, higher observed factors which represent higher risks, impacts or foreseen restrictions, account to higher evaluation levels in each criterion, which are weighted and summed to obtain a General Evaluation of Criticality (GE).

Criteria levels	1 - Very low	3 - Low	5 - Medium	8 - High	13 - Very high
The item is part of the critical path.	Not part of the critical path	Between very low and medium	Yes, weight equivalent to 3%.	Between medium and very high	Yes, weight greater than 6%.
Risk staff composition of crews	None	At least one person at slight risk, none at higher levels	1 or more people at moderate risk	Between medium and very high	More than one at-risk person, at least one with high risk
City's expected pandemic phase	Phase 5 – Normal activities and movement are allowed with no capacity restrictions	Phase 4 – Normal activities and movement are allowed with slight capacity restrictions	Phase 3 – Normal activities and movement are allowed with moderate capacity restrictions	Phase 2 – Normal activities and movement are allowed with significant capacity restrictions	Phase 1 - Full lockdown or only critical activities allowed with significant capacity restrictions
Average possible social distance in the work area	More than 8 m^2 per person	More than 6 m^2 per person	More than 4 m^2 per person	More than 2 m^2 per person	Less than 2 m^2 per person
Minimum guaranteed physical distance	More than 2 meters radial	-	Between 1 and 2 meters radial	-	Less than 1 meters radial
Level and type of ventilation of the area	100% open space	-	Enclosed with natural ventilation	Enclosed with need of mechanized ventilation	Enclosed not ventilated
Relative cost of the work-item in budget	Represents 1% of the project's budget or less	Between very low and medium	Represents close to 3% of the project's budget	Between medium and very high	Represents 6% or more of the project's budget
Necessary specialization in the work-item	Does not involve specialized manpower, resources or complex procedures	Only some specific tasks require moderately specialized manpower, resources or complex proceedures	Aproximately half of the tasks require moderately specialized manpower, resources or complex proceedures, none of them high	At least some specific tasks require highly specialized manpower, resources or moderately complex proceedures	Most tasks require highly specialized manpower, resources or highly complex procedures
Number of workers in average crew	1 to 4 people	5 to 6 people	7 to 10 people	11 to 14 people	15 people or more

Figure 1. Evaluation levels and assessment factors for each criterion of the instrument

Criterion	Weight	Response	Level	Weighted level
The item is part of the critical path.	21,30%	Yes, weight greater than 6%.	13 - Very high	2,769
Risk staff composition of crews	16,80%	1 or more people at moderate risk	5 - Medium	0,84
City's expected pandemic phase	15,10%	Phase 5 – Normal activities and movement are allowed with no capacity restrictions	1 - Very low	0,151
Average possible social distance in the work area	11,50%	More than 2 m^2 per person	8 - High	0,92
Minimum guaranteed physical distance	9,70%	Between 1 and 2 meters radial	5 - Medium	0,485
Level and type of ventilation of the area	9,00%	Enclosed with natural ventilation	5 - Medium	0,45
Relative cost of the work-item in budget	6,80%	Represents close to 3% of the project's budget	5 - Medium	0,34
Necessary specialization in the work-item	6,00%	At least some specific tasks require highly specialized manpower, resources or moderately complex proceedures	8 - High	0,48
Number of workers in average crew	3,80%	5 to 6 people	3 - Low	0,114
General Evaluation of Criticality (GE)			**6,549**	

Figure 2. Example of work item evaluation using the instrument

EVALUATION OF WORK ITEMS

Table 4 shows the global evaluation of the nine items by the three construction companies. Although the criticality rating ranges from 1 to 13, the work items' GE was rated in a range of approximately 4 to 8, i.e., they have a degree of criticality between medium and high level, as presented in the rubric of factors in Figure 1.

Table 4. Global Evaluation of criticality (GE) from the nine items

ID	Work item	Global evaluation
1.1	Preparation and placement of foundation reinforcement	7.27
1.2	Installation of basement wall formwork	5.48
1.3	Installation of tower reinforcement	5.06
2.1	Anchoring of foundation piles	5.46
2.2	Installation of basement wall formwork	4.21
2.3	Installation of basement wall reinforcement	4.45
3.1	Installation of basement wall reinforcement	6.39
3.2	Excavation of foundation piles	6.05
3.3	Concreting of basement wall	5.70

A sensitivity analysis was carried out using the correlation between the GE results from the nine items, and evaluation results obtain using three sub-sets of the criteria: (1) All but the city's pandemic phase (weight = 15.10%), since authority imposed restrictions may vary over time and depending on the region, (2) All but the participation in the critical path (weight = 21.30%), since different scheduling methods may lead to different critical paths, and (3) All but the city's pandemic phase and participation on the critical path (Combined weight = 36.40%). Figure 3 presents a scatter plot where x-axis represents the GE obtained using the instrument and y-axis shows the resulting scores of the evaluation in the three cases. The linear regression trend-lines from the three cases are also presented with their correlation values represented by their R^2 results to show if the work items could be assessed without the use of the criteria.

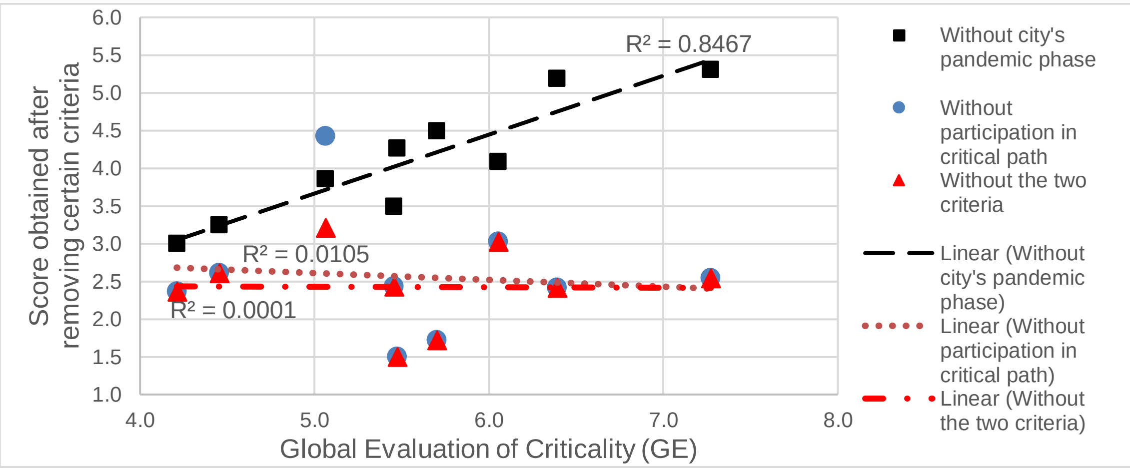

Figure 3. Sensitivity analyses of removing certain criteria from the evaluation

As Figure 3 exemplifies, removing the factors' evaluation associated with the expected pandemic phase of the city in which the project is being carried out would not drive significant differences in the evaluation. The high correlation between the GE scores and the scores obtained without considering the city's pandemic phase allows to infer that the instrument could be applied to prioritize work items from different projects in different cities, as well as assessing work items from the same project or region. On the other hand, removing the evaluation of the participation on the work item's related tasks in the critical path does affect the evaluation, as shown by the significantly low levels of correlation shown in figure 2. Hence, users should pay attention to comparing work items from projects using similar scheduling methods to prevent evaluation biases caused by the calculation of the item's weight on the critical path. Also, assessment of the item's participation and weight on the critical path should not be avoided since this criterion constitutes a fundamental element at the time of evaluating measures to mitigate project and safety risks.

CRITICALITY RANGES AND PROPOSED PREVENTIVE MEASURES

As presented in the research method section, at the end of stage 2, four criticality ranges were proposed. The first range represented the presence of mostly medium or lower-level factors in most of the criteria, hence, accounted for a GE≤5.0. On the opposite, the fourth range signaled the presence of high or very high criticality factors on most of the criteria, which would result in a GE≥8.0. The middle division was decided based on the effect caused by the three main criteria moving from a medium to high level, which represented moving for 5 to 8 points in criteria which accounted for approximately 53% of the weight. This movement would result in an increment of approximately 1.5 in the GE, hence, the middle division was set as GE=6.5, obtaining the four proposed ranges. Table 6 shows the proposed the set of measures recommended by the academic and industry experts to prevent health risks and related project impacts, depending on the criticality range of each evaluated work item.

Table 4. Set of measures proposed for each criticality range

Range	GE	Set of actions	Measures
1°	GE ≤ 5.00	Base	Implementing systematic periodic instances of planning and coordination
			Increasing safety equipment and sanitary protocols
			Implementing capacity restrictions and ensuring systematic control in work areas
			Implementing periodical mandatory Triage surveys
			Temperature measurement
2°	5.00 < GE < 6.50	Distancing	Base actions plus:
			Ensuring effective and efficient on-site coordination through methods such as the Last Planner® System
			Increasing control of interactions on specific locations through systems such as QR registration protocols
			Increasing social-distance prevention through use of alert systems such as distance detection bracelets
3°	6.50	Analytics	Distancing actions plus:

	< GE < 8.00		Implementing higher coordination protocols such as the use of Location Base Planning to prevent unnecessary interactions between crews
			Shielding at-risk crews and highly specialized crews by avoiding contact through coordination systems such as on-site Plan of Day (POD) apps
			Monitoring social-distancing and coordinated crew movement through systems such as Computer-vision and GPS real-time monitoring
4°	GE ≥ 8.00	Industrialization	Analytics actions plus:
			Using Building Information Modeling (BIM) systems to assess the opportunity to shield or extract critical elements from on-site construction
			Ex-situ construction or opting for the industrialized construction of the most critical activities

CONCLUSIONS

This research aims to propose a method for evaluating and prioritizing work items at the construction site, based on health risks, project impacts and current restrictions. An evaluation instrument was constructed through action research in collaboration with 11 academic and industry experts, to allow the compared assessment of work items from single or multiple projects and identify recommended preventive actions. The instrument uses a five-level nonlinear scale to rate the criticality from 9 relevant assessment criteria. These criteria were weighted through the use of Analytical Hierarchy Process in collaboration with the 11 experts, to obtain an Eigenvector representative of the compared weight of each criterion with a 91% consistency coefficient. The proposed method allows to classify each item into four criticality ranges and each of them presents a set of recommended preventive actions to minimize the risk of contagion and impacts on the project's goals.

Considering that the risk factors for COVID-19 contagion will lose relevance with time, the method proposed in the research represents an important step to face the different challenges or scenarios for the safety and health management in construction sites. It is possible to analyze specific risks such as handling and lifting of prefabricated elements, handling of chemical elements or other factors, which based on experts and professionals will be possible to quantify, measure and propose measures to mitigate such risks. Finally, the authors recommend that researchers continue this study by applying the instrument to additional items and projects, in addition to recommending new actions based on experience and literature research.

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