

# Selection of rework measurement methodology utilizing AHP method

## *Seleção de metodologia de mensuração de retrabalho através da utilização do método AHP*

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**Abstract:** Civil construction has high rework rates, which entails additional costs and delays in project deadlines. In this way, several authors and entities have studied the problem and sought solutions to try to quantify and minimize the consequences of reworking. Several rework measurement methodologies have been developed, including: Construction Industry Institute Reduction Rework Program, Best Productivity Practices Implementation Index of the Construction Industry Institute, Methodology of the Construction Owners Association of Alberta, and Measuring and Classifying Construction Field Rework. In this context, this article aims to propose a procedure, based on the multicriteria analysis method Analytic Hierarchy Process – AHP, to assist in the process of selecting the most appropriate rework measurement methodology to be adopted in subsectors of the civil construction industry. The proposed procedure was applied to the industrial assembly segment, and the Rework Reduction Program methodology presented the best results regarding the rework measurement according to five criteria selected for analysis (coverage, deployment, costs, data entry and system operation), being the most indicated for use.

**Keywords:** Rework; Civil construction; Industrial assembly; Multi-criteria analysis; AHP.

**Resumo:** A construção civil apresenta altos índices de retrabalho, o que acarreta em custos adicionais e atrasos nos prazos dos projetos. Deste modo, diversos autores e entidades têm estudado o problema e buscado soluções para tentar quantificar e minimizar as consequências do retrabalho, tendo sido desenvolvidas diversas metodologias para mensuração de retrabalho: Reduction Rework Program do Construction Industry Institute; Best Productivity Practices Implementation Index do Construction Industry Institute; Metodologia do Construction Owners Association of Alberta; e Measuring and Classifying Construction Field Rework. Neste contexto, o presente artigo tem como objetivo propor um procedimento, com base no método de análise multicritério Analytic Hierarchy Process – AHP, para auxiliar no processo de seleção da metodologia de mensuração de retrabalho mais indicada a ser adotada em subsetores da indústria da construção civil. O procedimento proposto foi aplicado no segmento de montagem industrial, e a metodologia Rework Reduction Program apresentou os melhores resultados em relação à medição de retrabalho conforme cinco critérios selecionados para análise (abrangência, implantação, custos, entrada de dados e operação do sistema), sendo assim a mais indicada a ser adotada.

**Palavras-chave:** Retrabalho; Construção civil; Montagem industrial; Análise multicritério; AHP.

## 1 Introduction

Civil construction has a high rate of waste and rework, which has an impact on costs, burdening contractors and contracts, delaying deadlines and reaching low quality levels (Grohmann, 1998). In order to verify the costs involved in reworking the total costs of the projects, Mastenbroek (2010)

carried out an extensive bibliographic review, which results are summarized in Table 1.

According to Mastenbroek (2010), reworking costs in construction, raised by several authors in different countries, vary between 1 and 10% of the total costs of the enterprise. Studies by the Construction Industry

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Institute (CII, 2013) also show that, on average, 5% of direct costs associated with total project costs are due to rework. Thus, with investments of \$ 1.7 trillion in 2014, it is estimated that the additional costs caused by rework in the construction industry in United States represent annual losses of approximately \$ 85 billion (BEA, 2014). Considering the same relationship for the Brazilian construction industry, reworking costs can be estimated at R\$ 16.30 billion, since investments in the sector were R\$ 326.1 billion in 2012 (IBGE, 2012).

According to the Construction Industry Development Agency (CIDA, 1995), rework is performing an extra task to meet requirements that have not been met. Nandhakumar & Ranjit (2015) consider that rework occurs when a product or service does not meet customer requirements and that efforts are performed for correction. Ashford (1992) understands that rework happens when an item is reprocessed to meet the original requirements, such reprocessing being done through complement or correction. Resuming, rework is the action taken to make an imperfect or out-of-specification component conform to the requirements or specifications (PMI, 2013).

Routines can occur at any stage of the construction process: in design, construction, transportation or manufacturing (Burati et al., 1992), as well as due to management failures, management or accounting errors. For Love et al. (1999) and Love & Li (2000), rework is essentially caused by failures, errors, omissions, damages and changes in specifications / drawings. The cited authors consider that: a) change is when there is a directed action changing the previously defined requirements; b) failure or error is when an activity in a process is executed imperfectly, failing to meet the required

requirements and c) omission is when any part of the constructive process, including design, manufacturing and assembly, has been stopped, resulting in deviations from the requirements. Thus, constructive errors are the result of wrong procedures and failures, while omissions can be caused by human failures or by climatic conditions or natural disasters (Love et al., 1999).

In complex environments such as the construction industry, which encompasses a productive chain with diverse sectors, and where several performers simultaneously carry out multiple interconnected activities, often errors, omissions and misunderstandings are committed, resulting in undesirable outputs that must be reworked (Hegazy et al., 2011). Particular aspects of the civil construction industry, which differentiate it from others, such as relatively long construction periods, the manufacture of unique products, the interference of a complex network of participants, the lack of monitoring of technological advances and deficiencies in the technical training of labor (Colombo & Bazzo, 2001), increase the possibility of reworking. In addition, some peculiarities of this industry in Brazil make the accuracy obtained even lower than in other countries (Fé Castro et al., 2014). The construction industry in Brazil has a low technological and management upgrading, as well as low levels of competitiveness and productivity, compared to developed country standards (Colombo & Bazzo, 2001; SEBRAE-MG, 2005). The sector is marked by problems regarding compliance with technical standards and standardization, as well as the intensive use of labor, and workers do not have adequate technical training (SEBRAE-MG, 2005). Such characteristics of the construction

**Table 1.** Cost of rework in relation to the total costs of the enterprises.

Author	Country	Cost
Cusack (1992 apud Mastenbroek, 2010)	Australia	10%*
Borroughs (1993 apud Mastenbroek, 2010)	Australia	5%*
CIDA (1995)	Australia	6,5%*
Lomas (1996 apud Mastenbroek, 2010)	Australia	>1%*
Love et al. (1999)	Australia	2.4 e 3.15%*
Love (2002)	Australia	6.4%*
CIDB (1989 apud Mastenbroek, 2010)	Singapore	5-10%**
Burati et al. (1992)	United States	12.4%**
Abdul-Rahaman (1993 apud Mastenbroek, 2010)	England	2.5-5%*
Hammarlund et al. (1990 apud Mastenbroek, 2010)	Sweden	6%**
Josephson & Hammarlund (1990, 1996 apud Mastenbroek, 2010)	Sweden	2.3-9.4%*
Josephson et al. (2002 apud Mastenbroek, 2010)	Sweden	4.4%*

\* % of contract value; \*\* % of design cost.

industry in the country contribute to increase the level of rework.

However, Hegazy et al. (2011) consider that the problem of reworking is even more complex in heavy construction projects because it involves an even larger number of stakeholders and because of the greater complexity of activities and interrelationships in this subsector of construction. According to ABRAMAT (2009), the construction industry is classified in three main sectors: buildings, construction materials and heavy construction, which is subdivided into urban infrastructure, transportation and industrial assembly. In 2014, there were 35,000 heavy construction companies in the national market, representing a growth of 39% compared to 2007, employing about 2% of the workforce in the country (SINICON, 2015). However, from March 2014 to March 2015, there was a 14% decrease in employment in the sector, which is higher than the average reduction in construction (SINICON, 2015). This fact is due to the economic problems that the country faces. Thus, due to the complexity and importance of the industrial assembly segment, this work focuses on this subsector of the construction industry.

In order to solve problems of time, cost and quality losses due to reworking in civil construction, several authors and entities have studied the problem and sought solutions for the misuse of equipment, labor, materials and financial resources in excess of those (Fé Castro et al., 2014). Among these authors and entities can be cited: Brazilian Association of Industrial Engineering - ABEMI, Construction Industry Institute-CII, Construction Owners Association of Alberta – COAA, Fayek et al. (2003, 2004), Love et al. (1999), Love (2002), Love & Smith (2003), Hegazy et al. (2011), Simpeh (2012), Hossain & Chua (2014), Fé Castro et al. (2014), Nandhakumar & Ranjit (2015). These studies propose different methodologies for the measurement, prevention, correction and mitigation of rework, such as the Measurement and Classification Construction Field Rework (Fayek et al, 2003), the COAA methodology - Construction Owners Association of Alberta (COAA, 2006), the CII's Reduction Rework Program (CII, 2011) and the CII's Best Productivity Practices Implementation Index (CII, 2013).

In this context, the present paper aims to study the main methodologies for measurement, prevention, correction and mitigation of reworking applied in the construction industry and, through a multi-criteria analysis, to identify the most effective methodology, considering certain criteria, to be adopted to measure rework in the segment of

industrial assembly, subsector of the construction industry. For this, the Analytic Hierarchy Process (AHP) method was used, which, according to Costa (2006), is one of the most scientifically recognized decision support methods under multiple criteria. This choice is also justified due to its applicability, simplicity and ease (Saaty, 1991).

The article is structured as follows: initially the research methodology adopted is presented. Next, we present the main methods of rework measurement, the data analysis and, finally, the main conclusions of the research.

## 2 Methodology

The objective of the research is to evaluate, among methodologies for measurement, prevention, correction and mitigation of rework, which is the most effective in the industrial assembly segment, subsector of heavy construction, one of the civil construction sectors. This study covers the Brazilian heavy construction segment. In this way, the work methodology for the development of this research was conceived in four stages.

In the first stage, the bibliographic review was carried out, identifying the main methodologies for measurement, prevention, correction and mitigation of rework to be applied in civil construction. The main sources of consultations were: Capes periodicals, Brazilian and foreign universities (UFRJ, UFF, UFMG, UFRGS, University of Texas), technical organizations (CII, COAA, PMI, ABNT etc.), governmental and private organizations (IBGE, ABRAMAT / FGV, BNDES, SEBRAE-MG, SINICON, FIESP, ABEMI) for search of data and articles related to rework, civil construction, industrial assembly, productivity, rework measurement. The bibliographical research in the mentioned sources made possible to collect information on the researched subject and, mainly, the identification, characterization and examination of the main methodologies, currently available, for measurement, prevention, correction and mitigation of reworking. Section 3 presents these main methodologies, proposing general criteria for the hierarchical selection of available rework measurement methodologies alternatives.

The specialists are civil engineers who work directly in the industrial construction segment and researchers on the subject, who contributed with their expertise in the topic to define the criteria. Six criteria were proposed for the analysis: Scope; Implantation; Costs; Data entry; System Operation and Results, as presented in Section 4.

In the third stage of the research, weights were weighed against the adopted criteria, by means of judgments, along with the Saaty scale, of criteria and alternatives, made by the specialists, for each

alternative of methodology considered. This condition aimed to propose a hierarchical evaluation of the different remediation measurement methodologies available due to their relevance and eventual success of implementation in the field researched. For this purpose, the AHP (Analytic Hierarchy Process), as defined by Saaty (1991), was applied through the software SuperDecisions.

One of the first methods developed to solve decision-making problems in the presence of multiple quantitative and qualitative criteria, the AHP evaluates the relative importance of the criteria, compares the alternatives for each criterion, which, in this case, are the methodologies for measuring rework, in addition to determining a decreasing scale for the alternatives considered (Marchezetti et al., 2011). The justification for choosing AHP in decision-making is its extensive applicability, simplicity, ease of use and great flexibility (Ho, 2008). Still, Costa (2006) considers AHP as one of the decision-making methods under multiple criteria that are more scientifically recognized.

The fourth stage of the research allowed the definition of a hierarchical scale of the alternatives of methodologies available for rework measurement in the civil construction industry, from the most appropriate to the least adequate, based on the sum of the weights obtained for each selection criterion for each alternative.

Finally, the literature review allowed the available methodologies selection for rework measurement in the segment studied and, therefore, the adoption of criteria to be evaluated and hierarchized. In turn, the application of the AHP method made it possible to

calculate weights for each alternative in relation to the proposed criteria. The result of calculated weights sum, based on the criteria adopted for each rework measurement methodology, allowed the different methodologies hierarchy in descending order, thus guiding the priority in the choice to be implemented.

Figure 1 presents a schematic of the criteria and alternatives of methodologies adopted for rework measurement in civil construction.

### 3 Methodologies for the measurement, prevention, correction and mitigation of the jobs

In this section, the main methodologies for measurement, prevention, correction and mitigation of reworking, applied in the construction industry, identified from the literature review are presented.

#### 3.1 Reduction Rework Program, Construction Industry Institute (CII, 2011)

In 2003, the Construction Industry Institute initiated a program to reduce rework in Industrial Assembly projects to reduce rework, increase project performance and increase overall productivity (CII, 2011). This effort resulted in the identification and description of factors that cause rework. A checklist was created regarding the quality of processes involved in the project cycle, to reduce the chance of rework (CII, 2011). The result was called Rework Reduction Program-RRP (CII, 2011). The RRP is a measurement and monitoring system

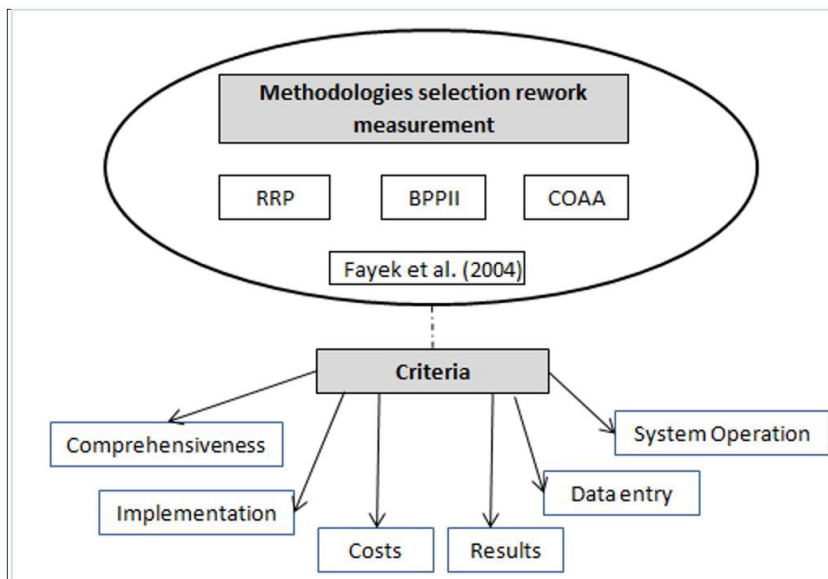


Figure 1. Criteria adopted for the hierarchy of measurement methodologies. Source: Authors (2015).

of the level of rework extension in enterprises sites. Only when rework is measured its impact can be known, its extent, and measures taken to eliminate its causes (CII, 2011).

The RRP consists of four steps: 1) rework measurement of rework and causes classification; 2) rework and causes analysis; 3) planning of corrective actions and 4) integration of corrective actions within the general enterprise management system. The RRP considers only rework executed on the enterprise site, not focusing on rework performed during the design, supply, fabrication or transport phases for the site (CII, 2011). The RRP objectives are: 1) improve the work quality by finding the root cause of rework, analyzing and implementing measures to avoid repetition; 2) communicating lessons learned to other enterprise ventures; 3) decrease pressure in the workplace by making the work done right the first time; and 4) allow a comparison of the company's performance against the segment's metrics. For this, indexes were created that allow this comparison.

The development process of RRP has as inputs: organizational processes, scope definition, project management plan, the unit cost of the resources and the enterprise schedule. The process is then developed through the steps already described and the outputs are: lists of classification of rework, analysis of rework occurrence, analysis of rework impact on costs and schedule, updated corrective actions. The RRP considers that each cycle step functions as a prerequisite for the next and that each corrective action plan produces improvements for the system as a whole. In addition, the system has an educational purpose. It is through the data compilation that it becomes possible to verify the rework negative effects in relation to the work's financial and time objectives (CII, 2011).

The first stage execution, rework measurement and classification of causes, is done with the following tools: existence of organizational assets (lessons learned, rework data in other enterprises, etc.); Analytical design structure; Rework classification structure; Rework data monitoring and archiving; Documentation review; Determination of causes list (through brainstorming and interviews) and judgment. The outputs of this phase are updated list of rework categories and relevant data (costs, delays, frequency, etc.) (CII, 2011). Rework and causes analysis is performed by defining project scope, schedule and cost management plan, rework classification list, unit resource prices. At this stage, the following techniques are used: document review, data collection, quantitative and monetary analysis. The results are as follows: rework trends and their impacts on deadlines, costs and quality (CII, 2011).

For the third step, planning corrective actions, using inputs such as: rework classification list, rework trends

and their impacts on deadlines, costs and quality, Resource limitations management, and techniques such as strategy definition for reduction of rework, change management procedures definition and training of human resources to improve productive efficiency, a plan of corrective action is reached. Corrective action planning has the important function of determining and designing corrective actions necessary to eliminate the causes of rework (CII, 2011).

For the success of RRP, the process must be integrated with the enterprise general management system. The CII (2011) emphasizes that a system for surveying, processing, cataloging, analyzing and disseminating causes of reworking and eliminating them should be created through an integrated system, which is presented in the guide "A Guide to Construction Rework Reduction", edited by the CII in 2011.

CII (2011) also created formulas for monitoring and analyzing performance of hours and costs involved in reworking, through graphics. The formulas are:

Rework cost rate = Total rework cost for a given work package / Aggregate total value for a given work package.

If dismantling and rebuilding are required to carry out rework, these values should be considered in the calculation.

MH rate used in rework = total MH expenditure on rework for a given work package / aggregate total value for a given work package

CII considers that, through implementation of RRP will be possible to determine the impact of rework on enterprise deadlines, costs and quality. In addition, through the knowledge of the root cause, will be possible to establish corrective actions, aiming at eliminating losses from rework and, consequently, increasing productivity (CII, 2011).

### 3.2 Best Productivity Practices Implementation Index, Construction Industry Institute (CII, 2013)

The Best Productivity Practices Implementation Index (BPPII), a program launched by the Construction Industry Institute, is a program that aims to increase productivity of activities developed on infrastructure projects sites. The BPPII considers that only what is measured is improved. BPPII classifies planning and implementation of practices that have potential to improve productivity during infrastructure projects construction, thereby reducing rework levels. BPPII should be used on construction phase early stages (CII, 2013).

For CII (2013), BPPII usage allows: a) to define best practices that increase productivity, which must be planned and implemented in the enterprise construction phase; b) a checklist is established determining level of planning and implementation

of these best practices; and (c) strategies to enhance the effectiveness of these best practices.

The CII (2013) recommends that BPPII be used at the end of Front End Planning and at the beginning of the implementation phase, to assist in Project Execution Plan preparation, BPPII is composed of a data sheet (in MS Excel) with the following parts: introduction, user's guide, description of BPPII, having as entry - BPPII classification and output - evaluation report. The BPPII scoring criterion considers 61 elements to be evaluated and each of them has a weight to be considered in the final evaluation. This weight was calculated taking into account the influence of each of these elements on productivity and were determined through a survey conducted with highly experienced professionals in infrastructure projects. These professionals were asked to determine the importance of each element, and the average that was used to calculate the value of each element was finally calculated (CII, 2013). The research was validated through data collected from several infrastructure projects, divided into two groups (with high and low values of BPPII score), and an ANOVA test was performed with a confidence level of 95% to prove the statistical significance between these two groups. The test result confirmed that the difference between the two groups is statistically different, validating the result. This validation allowed CII to conclude that ventures with better BPPII scores have better levels of productivity (CII, 2013).

BPPII comprises 6 categories and 20 sections. Each section comprises between one and five elements that correspond to best practices recognized by the construction industry (CII, 2013). The categories are as follows:

- a) Materials Management (comprising three sections and nine elements);
- b) Construction and Logistics Equipment (comprising two sections and seven elements);
- c) Execution Approach (comprising four sections and fourteen elements);
- d) Human Resources Management (comprising five sections and eleven elements);
- e) Constructive Methods (comprising three sections and twelve elements);
- f) Health, Safety and Environment (comprising three sections and eleven elements).

The BPPII evaluation system takes into account planning and implementation level of each of the 61 elements and values are given ranging from zero to five. The zero means that the element is not applied and the five that the practice is fully planned

and applied. CII considers that those enterprises that have higher than 50% evaluations have the right level of planning and implementation of best practices, and should achieve better results and reduce rework levels (CII, 2013). However, CII points out that there are restrictions on the use of BPPII for certain types of enterprises such as industrial enterprises and buildings (CII, 2013).

This article does not address the structure of the categories and sections, definitions of each category, section and element that is found in document CII-BPPII- Best Productivity Practices Implementation Index, edited by CII in 2013.

### 3.3 Construction Owners Association of Alberta Methodology (COAA, 2006)

The Construction Owners Association of Alberta (COAA) has established a methodology for measuring and reducing rework, called Project Rework Reduction Index (PRRI). PRRI serves to measure enterprises in relation to rework, considering known and significant causes of rework at any stage of the enterprise's life cycle (COAA, 2006). The enterprise performance in relation to rework level is measured considering five key areas that may have rework. They are Engineering and revisions, Construction planning and schedules, Leadership and communication, Supply of equipment and materials and Training of human resources. These five areas are detailed in 20 potential causes of rework. These 20 causes are, in COAA's evaluation, the most important ones for rework appearance (COAA, 2006). Figure 2 details these causes in relation to areas.

Projects evaluation in relation to rework is done through a multiple choice questionnaire containing between 29 and 90 questions. There are five questionnaires, one for each phase of the enterprise life cycle. These phases are: Completion of the Design Build Memorandum (DBM), Emission of engineering specifications, 20% completed from the detailed engineering phase, 20% completed from the construction phase, 50% completed from the construction phase. The classification, through PRRI, takes into account the possible causes of rework, determined through the questionnaires. The answers are evaluated by mathematical weighting. That is, the higher the degree obtained, the less likely it is to rework. The index obtained has a relative value and should be understood as indicative of rework level trend (COAA, 2006). Through periodic evaluations of results obtained by questionnaires, it is possible to elaborate items such as the "Tile Chart" and the "Dashboard Chart" that allow discussion, evaluation and review of enterprises situation in relation to rework, allowing that actions are taken to eliminate

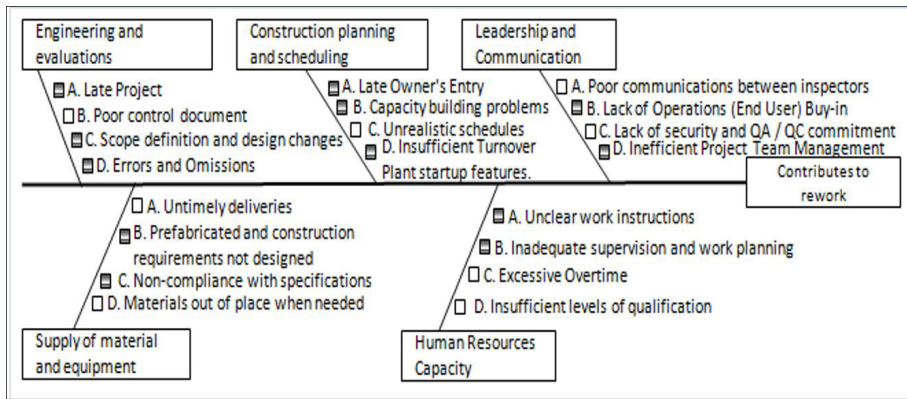


Figure 2. Classification of causes of rework according to COAA. Source: COAA (2006).

their causes (COAA, 2006). Next, Figure 3 illustrates an example of a “PRRI Dashboard Chart”, which through radar graphs illustrates the likelihood of rework (COAA, 2006).

Through the Dashboard Chart, as shown in Figure 3, it is possible to issue a trend graph of rework in the enterprise, allowing trends analysis for the top five causes of rework, as illustrated in Figure 4.

PRRI also offers suggestions for eliminating rework through best practices to be introduced and practical solutions for improvement of root cause re-management and elimination (COAA, 2006).

### 3.4 Measuring and Classifying Construction Field Rework (Fayek et al., 2004)

Fayek et al. (2004) conducted a study to establish good practices for construction companies to reduce excess of rework in sites that had been happening in the projects carried out in Canada. The authors went back to the studies developed by Love et al. (1999), Love & Li (2000), Love (2002) and Love & Smith (2003).

Fayek et al. (2004) established as a basic principle that to rework to be reduced, one must first identify it, measure it and understand its root cause. In this paper, Fayek et al. (2004) found several definitions of rework and measurement indices proposed by Ashford (1992), Love & Li (2000), Rogge et al. (2001) and COAA (2001) for definitions and Burati et al (1992), Gibson and Dumont (1996), CII (1997), COAA (2001) for classification of causes and measurement. In this survey, Fayek et al. (2004) found that, although there were several studies on reworking, there were still no standards for rework measurement and classification that were accepted by industrial construction and assembly organizations. Thus, they decided to create a methodology for measurement and classification of

rework executed during projects construction phase, which should be widely accepted by the Canadian construction industry.

The methodology proposed by Fayek et al. (2004) consists of: a) definition of standards for rework performed in the construction phase; b) establishment of a definition for rework performed in the construction phase that is accepted by companies in the segment; and c) establishment of a classification system and identification of the causes of rework in the construction phase. The authors conducted a pilot study in a large enterprise in the Province of Alberta in Canada, aiming to obtain data that allowed methodology development, meeting the three proposed objectives. They concluded that “rework are activities that must be redone or results from activities that have to be removed regardless of origin, provided there has been no change of scope or some change in specification.” This definition is very close to that accepted by CII (2011). The one developed by COAA (2001) and known as fishbone inspired the rework clarification system suggested by Fayek et al (2004). The classification proposed by the authors is presented in Figure 5.

Fayek et al. (2004) propose a procedure for data collection, presented in Figure 6. This procedure should be used by companies to collect data referring to rework performed during construction phase. To facilitate data collection in the field, they developed a collection system called Field Rework Data Collection System (FRDCS) using Microsoft Access 2000 software with a Microsoft Visual Basic 6.0 interface. This system allows elaboration of several graphs, through which those responsible for the construction phase of the enterprise analyze rework trends, their main causes, impacts on costs and deadlines and can develop strategies to reduce rework.

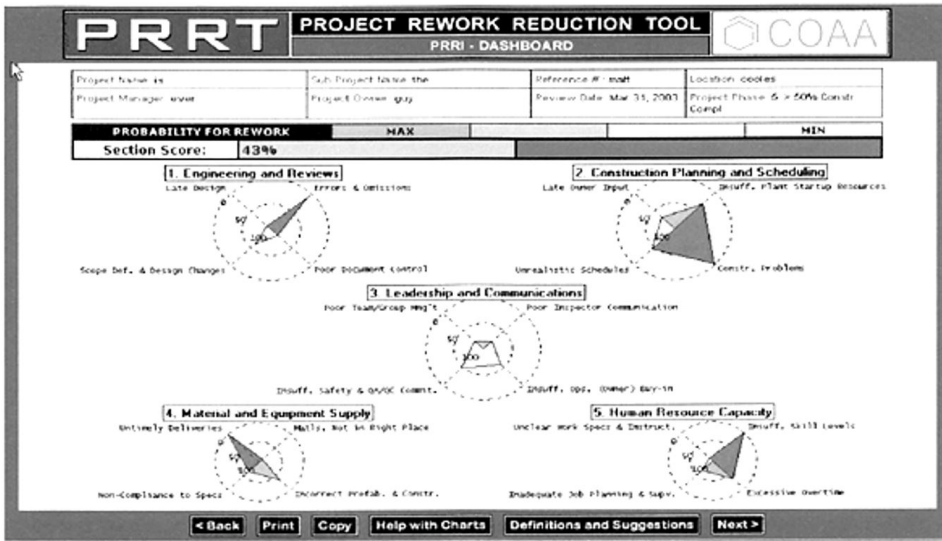


Figure 3. Example of PRRI Dashboard Chart. Source: COAA (2006).

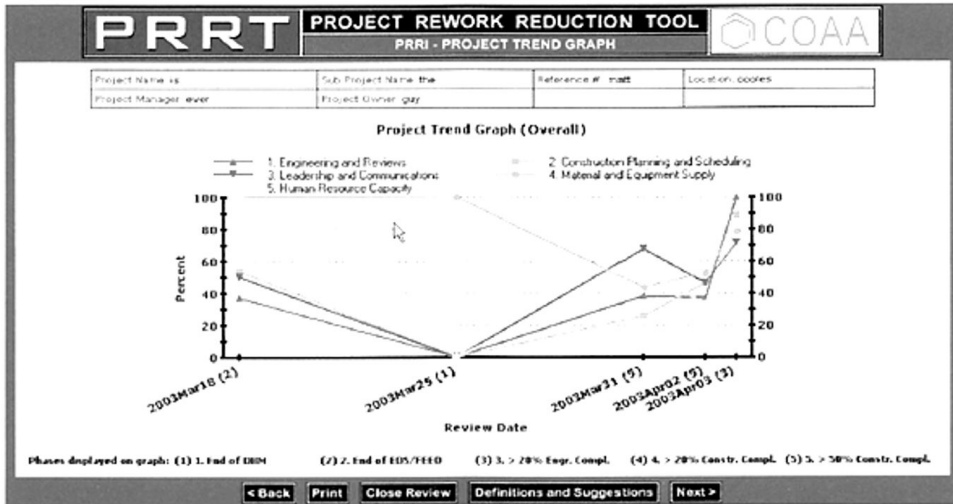


Figure 4. Example of trend graph. Source: COAA (2006).

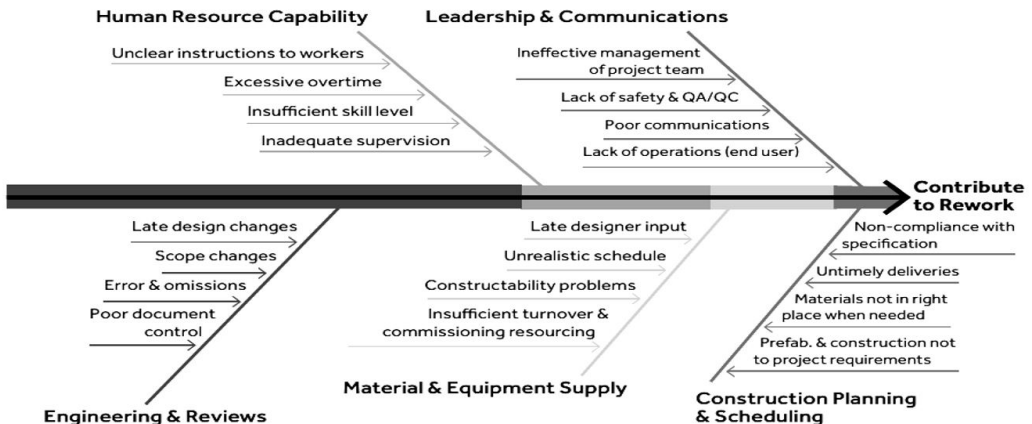


Figure 5. Suggestion of causes of rework. Source: Fayek et al. (2004).



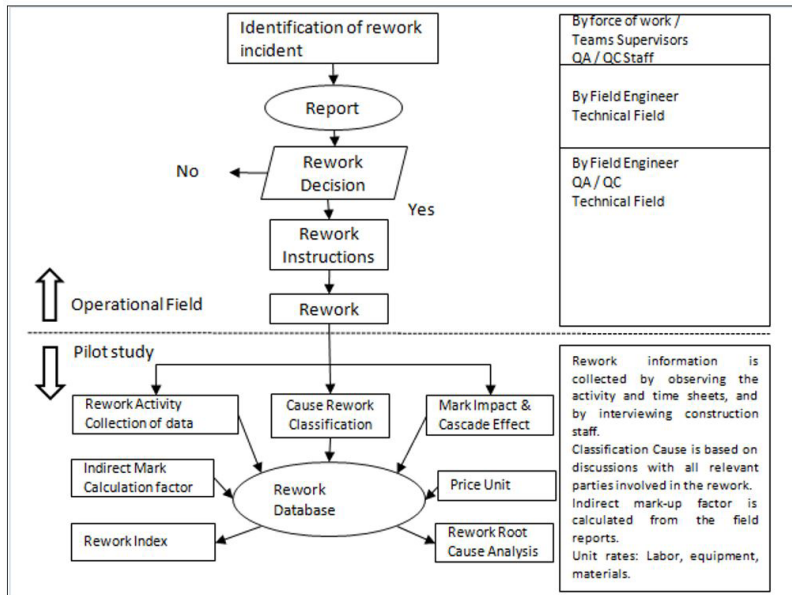


Figure 6. Procedure used for data collection. Source: Fayek et al. (2004).

### 4 Analysis of results

From the literature review, the main methodologies of rework measurement discussed in Section 3 were raised and examined. They are Reduction Rework Program of the Construction Industry Institute (CII, 2011); Best Productivity Practices Implementation Index of the Construction Industry Institute (CII, 2013); Methodology of the Construction Owners Association of Alberta (COAA, 2006); and Measuring and Classifying Construction Field Rework (Fayek et al., 2004). These four methodologies are the alternatives to be inputted into the AHP structure. To facilitate this information input in the software SuperDecisions, each model was abbreviated by acronyms: RPCI, BPPII, COAA and Fayek et al. (2004).

Once the alternatives were defined, criteria to be used to select the available alternatives was chosen. The criteria determination was based on interviews with 5 (five) specialists who have been working in the industrial assembly sector for more than 10 years and with three (3) academic researchers studying the subject. All respondents are civil engineers with postgraduate courses. The experts contributed with their experience to define the criteria. Six (6) criteria were considered:

- **Comprehensiveness:** methodology limitation in relation to the enterprise life cycle, observing its application in all the stages of the cycle;
- **Implementation:** ease of methodology implementation in enterprises, considering speed, number of people involved, ease of training,

need for changes in existing processes and availability of management tools and systems;

- **Costs:** total cost of ownership, when all costs involved in the methodology application are considered, i.e. acquisition, deployment, training and operation costs;
- **Data entry:** facility for obtaining and inserting data in each methodology system;
- **System Operation:** considering concepts of reliability, availability and maintenance for the operating systems of the different methodologies;
- **Results:** considering accuracy, reliability, ease of obtaining and interpretation of the indicators obtained by the methodology.

Based on the information of the alternatives and the criteria, the AHP hierarchy was constructed, presented in Figure 7, which, according to Saaty (2008), can be structured in a decision tree.

For the judgement, a questionnaire was prepared and distributed to 8 (eight) experts, along with the Saaty scale, criteria and alternatives. The scale used is the one proposed by Saaty (1991), composed of absolute numbers from 1 to 9. The experts made the judgments between criteria and between the alternatives in relation to each criterion, resulting in a paired matrix of the elements of the hierarchy. The authors intermediated the process and, based on the answers of the experts to the questionnaires, filled in the data in the software SuperDecisions, developed by Thomas Saaty. This computational

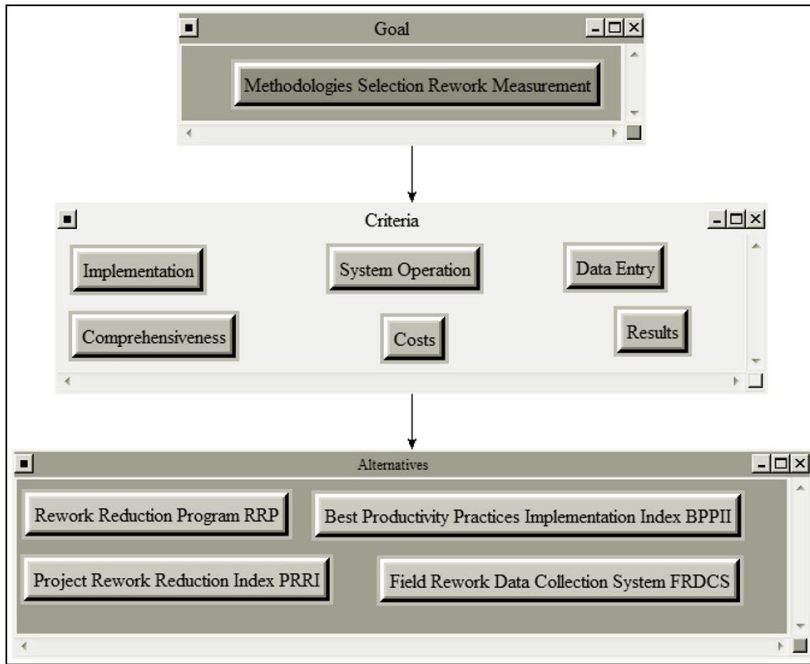


Figure 7. Hierarchical structure. Source: Authors (2015).

tool was used to analyze the AHP method, to verify inconsistencies and analyzing results.

According to Al-Harbi (2001), it is necessary to evaluate the expert judgments consistency, which Saaty (1991) called as an inconsistency index (CR). According to Hsiao (2002), if the CR value is higher than 10%, the judgments are inconsistent and should be reviewed. In the present study, the criteria and alternatives judgments for each criterion were consistent; since the RC calculated in each matrix presented a value lower than 10%.

In the judgment result for the considered criteria hierarchy, the inconsistency index presented was of 0.09633, being acceptable. Table 2 presents the indexes of inconsistencies obtained for each criterion. It should be noted that all indices are less than 0.1 and are therefore acceptable. Table 3 shows the decreasing order of importance of the methods in relation to each of the criteria.

Figure 8 shows the result of priorities, both for the methods under analysis and for the criteria adopted. Based on the information in Figure 8, the methodology selected by the AHP to be used to measure rework is the RRP, which appears first, with a weight in the hierarchy of 45.044%. Second, the PRRI method, with 24.596%; Third, the BPPII method, with 18.429% and, finally, the FRDCS method, with 11, 931%. Thus, the prioritization of the methods, obtained by the AHP, is RRP> PRRI> BPPII> FRDCS.

In order to finalize the application of the AHP, we performed the global analysis of the relative weights of the criteria in relation to the objective and the

Table 2. Index of inconsistency for the criteria.

Criteria	Ínconsistency index
Comprehensiveness	0.07017
Costs	0.06948
Data Entry	0.00772
Implementation	0.08062
System Operation	0.09363
Results	0.03120

Source: Authors (2015).

Table 3. Decreasing order of importance of methods for each criterion.

Crítério	Importância dos métodos
Comprehensiveness	RRP > PRRI > BPPII > FRDCS
Costs	PRRI > BPPII > RRP >FRDCS
Data Entry	PRRI > BPPII > RRP >FRDCS
Implementation	RRP > BPPII > PRRI > FRDCS
System Operation	BPPII > RRP = PRRI > FRDCS
Results	RRP >PRRI > BPPII = FRDCS

Source: Authors (2015).

performance of the alternatives with respect to the criteria. For the selection criteria of the methodology of measurement of rework, it is verified that the most Important is the Result criterion with 43.462%, followed by the order: Coverage with 22.88%, System Operation with 11.653%, Deployment with 10.249%, Costs with 7.072% and, finally, Data Entry with 4.685%. Thus, as shown in Figure 8, the criteria in descending order of importance are Results> Scope> System operation> Deployment> Costs> Data entry.

Name	Normalized by Cluster	Limiting
Best Productivity Practices Implementation~	0.18429	0.092143
Field Rework Data Collection System FRDCS	0.11931	0.059653
Project Rework Reduction Index PRRI	0.24596	0.122982
Rework Reduction Program RRP	0.45044	0.225221
Comprehensiveness	0.22880	0.114402
Costs	0.07072	0.035358
Data Entry	0.04685	0.023423
Implementation	0.10249	0.051244
System Operation	0.11653	0.058265
Results	0.43462	0.217308
Methodologies Selection Rework Measurement	0.00000	0.000000

Figure 8. Results priorities. Authors (2015).

### 5 Final considerations

Rework occurrence in projects causes additional costs, which have a significant impact on total costs. Particularly in heavy-duty industrial projects, problems derived from rework are more complex. Thus, in order to quantify and minimize reworking consequences, several authors and entities have studied the problem and sought solutions for misuse of equipment, labor, materials and financial resources in quantities greater than those required. For this, several methodologies were created and explained throughout the article. However, it is extremely important that they be studied and defined which is the most effective.

In this context, the present paper used the AHP method, one of the best-known and used decision support methods, to determine the most effective methodology for measuring, preventing, correcting and mitigating rework to be applied in the industrial assembly segment. Therefore, it was determined that the Rework Reduction Program methodology is the one that presents the best results in relation to rework measurement according to the selected criteria, being thus the most indicated to be adopted in the industrial assembly segment. Because of the analysis, the ordering of the criteria for selection of the most efficient methodology was also obtained: Result followed by Scope, System Operation, Deployment, Costs and Data Entry.

Finally, AHP application to select rework measurement methodology allows a more qualified choice to be made on the rework measurement

methodology to be adopted, thus contributing to reduce the levels of bias, subjectivity and arbitrariness of the process. However, it should be emphasized that the judgment quality made by the decision makers is an important aspect in the evaluation. Therefore, it is recommended that, before the final decision of the Rework Reduction Program, a test be developed using the chosen methodology to demonstrate its full potential. Also, as recommendations for future work, the application of other multicriteria decision-making methods and the development of studies from the perspective of transaction costs economics, part of the research of the new economy of the institutions, to select methods of rework.

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