A product/process model-based system to produce work instructions

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ABSTRACT:

The state-of-practice method to produce formal and good work instructions is time intensive, error prone and produces instructions with inconsistent format and content. These problems force contractors to rely on verbal communication to deliver work instructions to their laborers despite the negative impacts of this informal communication on productivity, rework, workface questions, and safety. This paper presents an automated system – FIPAPM, Field Instructions from Product And Process Models – to produce work instructions for laborers of cast-in-place (CIP) concrete construction. The FIPAPM system extracts design information from product models and construction information from process models based on the work scope of the activity for which the work instruction is produced. The presented system proved to produce work instructions faster, more correctly, and more consistently than the state-of-practice method. Therefore, FIPAPM enables contractors to produce formal, good-quality work instructions on a daily basis reducing field communication problems of informal, verbal work instructions.

1 MOTIVATING PROBLEM

The state-of-practice method to produce formal, good-quality work instructions for a particular construction activity consists in a person or group: (i) selecting the proper design information from the project's set of construction drawings or product models; (ii) establishing the best practice (construction steps and equipment and tools needed) to perform the respective construction activity; and finally, (iii) deciding on a format to communicate this information to the laborers and putting the selected design and construction information into that format. This method presents three main challenges:

- Effort: from our observations, it takes between 1 and 2 hours to produce a good work instruction.
- Error proneness: producing good instructions requires integrating information from different sources (e.g., different drawings, specifications, 3D models) which presents a high risk of making mistakes.
- Inconsistency: the construction information depends on the person or group producing the instruction, and the output of the method (i.e., work instruction) is not predefined. Therefore, work instructions that result from the state-of-practice method are inconsistent in format and content.

These challenges force contractors to rely on verbal communication and the project's set of construction drawings to tell its laborers what to do and how to do it. However, these informal, verbal instructions negatively impact the field work as described below.

- Productivity: the poor quality of construction drawings (Gao et al. 2006, Makulsawatudom & Emsley 2003, Kagan 1985) and poor communication skills at the jobsite (Makulsawatudom et al. 2004) lower labor productivity.
- Workface questions: we observed during a previous study (Mourgues et al. 2007) that the verbal communication of instructions leads to laborers having many questions when executing their work. These questions, such as how to perform a particular operation and how much material they need for a particular work scope, reduce productivity and the product quality.
- Rework: poor instructions also increase rework. For example, Kaming et al. (1997) identified them as the second cause of rework in Indonesia.
- Safety: during our previous research, we observed that this poor communication of instructions produces unsafe situations since laborers do not fully understand certain safety procedures and fail to apply the general safety training to the specific tasks they are doing.

To reduce these field problems, we developed a system to produce better quality work instructions that addresses the challenges contractors face with the state-of-practice method. This system leverages the information contained in digital product and process models of construction projects.

This paper describes the developed system, its user interface and its impacts. The paper also explores several formalizations or schemas of information that provide the base for the presented system.

2 INFORMATION SCHEMAS

To assess the applicability of existing information schemas we considered whether the definition of information elements in a schema allows identifying the information related to the content and format of good work instructions. As a reference of good work instructions, we defined a content and format template (Fig. 1) –that we call field instructions template– based on field testing and a set of characteristics of good instructions we derived from the literature (Antifakos et al. 2002, Austin et al. 1995, LeFevre & Dixon 1986, Heiser et al. 2003, Agrawala et al. 2003, Smith & Goodman 1984, Oglesby et al. 1989, Emmitt & Gorse 2003). This template has four sections: drawings, with the relevant graphical information; instructions, with a set of construction steps to perform the activity; equipment & tools, with a list of equipment and tools needed to perform the activity based on the construction steps; and BOM (Bill Of Materials), with the quantity of materials for the activity's work of scope.

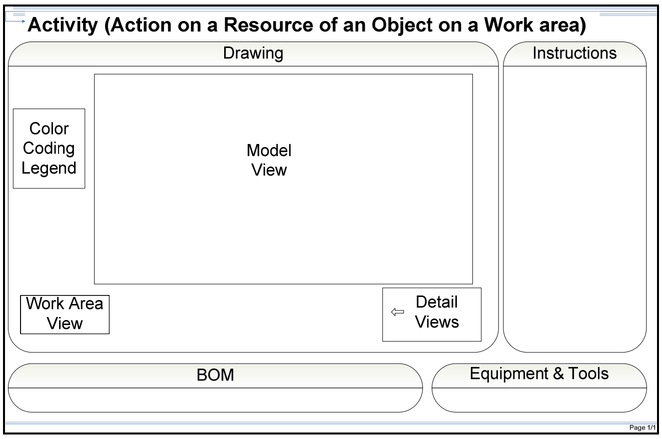


Figure 1. Field instructions template.

Therefore, the activity information schema must define a work scope that identifies the design and construction information needed to produce a field instruction (i.e., work instruction based on the field instructions template). On the other hand, the product and process information schemas must enable the extraction of that design and construction information from the product and process models.

The OAR (Object-Action-Resource) activity schema (Darwiche et al., 1988) contains most of the information elements needed to define an activity's work scope for field instruction purposes. However, this schema lacks a description of the work area where the activity occurs. The three levels of location breakdown structures (LBS) for typical building projects (Seppänen and Kenley, 2005) define this work area well. These levels are: buildings or structurally independent parts of buildings; floors; and rooms, apartments or other spaces.

In the domain of process information schemas, flowcharting (ISO, 1985) not only provides the basic information elements that most of the literature includes (i.e., activities, precedence relationships, resources) but also an information element that is fundamental for our purpose: decision elements. However, flowcharting and the rest of the literature lack information elements that define the format and content of work instructions for a particular construction process.

Finally, in the domain of product information schemas, Industry Foundation Classes (IFC) (IAI, 2008) includes all the product information elements needed to basically describe the building components of a field instruction (i.e. ifcBuildingElement, ifcMaterial, ifcBuilding, ifcBuildingStorey, ifcZone).

3 PRODUCT/PROCESS MODEL-BASED SYSTEM TO PRODUCE WORK INSTRUCTIONS

The FIPAPM system – Field Instructions from Product and Process Models – extracts project-specific design information (i.e., geometric information, quantities, model views) from the project's 3D model and company's level construction information (i.e., best construction practices, equipment and tools) from the company's process models. With this information, the FIPAPM system populates the field instruction template creating an activity-specific field instruction (Fig. 2).

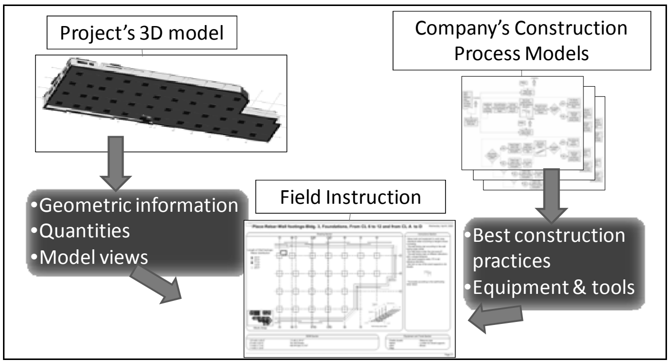


Figure 2. General view of the FIPAPM system.

The user of the FIPAPM system (e.g., project engineer, superintendent) uses the interface depicted in Figure 3 to capture the work scope of the activity.


Activity Input

Field Instructions

Cast-in-place concrete

What are you going to do? (Action + Resource): Place-Rebar

On what element? (Object): Wall footings

All Objects

Where? (Work Area)

Building: Building 3

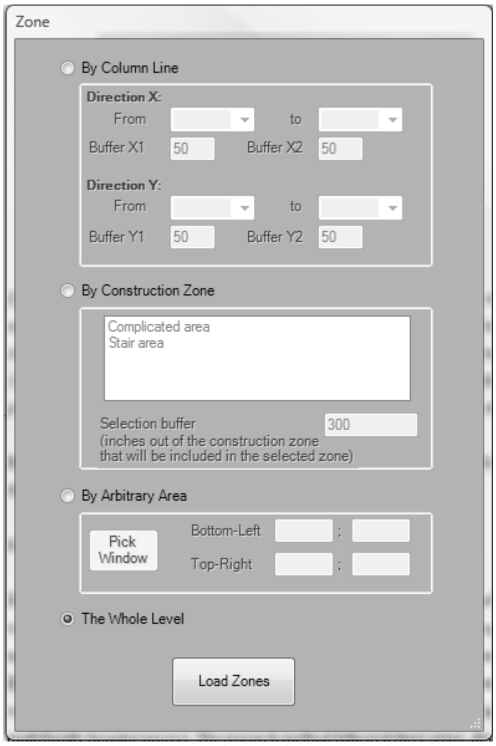
Select Level: Foundations

Select Zone: The whole level

Figure 3. Snapshot of interface to define the work scope of the activity that needs a field instruction.

The system user specifies what a crew will do using an “action-resource” tuple (top frame in Fig. 3). Examples of this tuple are place-rebar, set-forms, pour-concrete, etc. Then, the user selects the building element or object that the crew will work on (middle frame in Fig. 3), for example, wall footings, columns, slab-on-grade, elevated deck, etc. Optionally, the user could select a subset of a particular building element, for example, a particular type of column. Finally, the user must define the work area where the crew will work (bottom frame in Fig. 3). To define this area, the user must select a building, a level and a zone. The options for building names and levels are extracted automatically from the product model. Zones can be defined in four ways (Fig. 4):

- By column line: using column lines as a reference grid and buffers to specify distances from those lines.
- By construction zone: using areas defined by construction constraints or concerns. For example, concrete pours of a post-tensioned slab, areas that present a particular complication for the construction, etc.
- By arbitrary area: using a selecting box directly in the product model.
- The whole level: using the complete level that the user previously selected.


Zone

○ By Column Line

Direction X:
From: to:
Buffer X1: 50 Buffer X2: 50

Direction Y:
From: to:
Buffer Y1: 50 Buffer Y2: 50

○ By Construction Zone

Complicated area
Stair area

Selection buffer (inches out of the construction zone that will be included in the selected zone): 300

○ By Arbitrary Area

Bottom-Left: ;
Top-Right: ;

● The Whole Level

Figure 4. Snapshot of interface to define zones.

Once these selections are made, the activity’s work scope will be defined as an “action-resource-object-work area” tuple. In our example, this tuple is “place-rebar-wall footings-building 3, foundations, the whole level.” Based on this work scope, the FIPAPM system selects the process model that applies to the construction process implicit in the work scope as the library of construction process models is organized by “action-resource-object” tuples. Figure 5 depicts an example of a construction process model for our example activity.

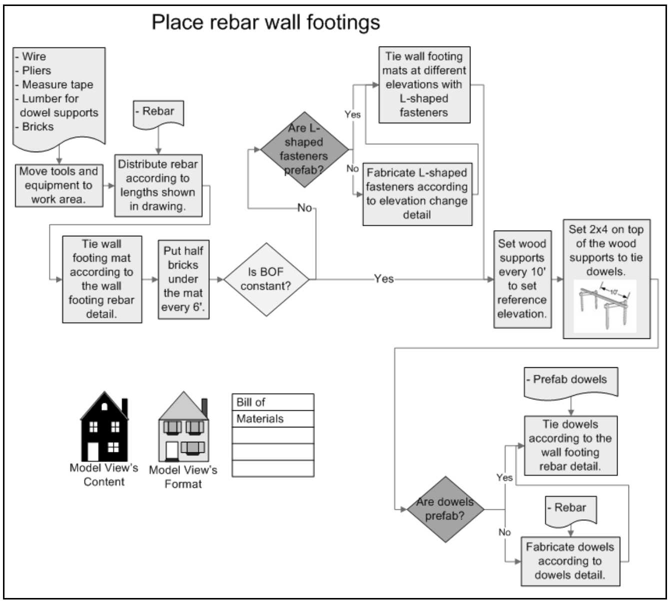


Figure 5. An example of a construction process model for “place-rebar-wall footings.”

The process models are generic as they include different alternative scenarios that depend on project-specific conditions (e.g., water table elevation, wall height, column type, weather, local building regulations). These scenarios are defined by decisions represented by the diamond-shaped elements in the process model. These decision elements can be of two types.

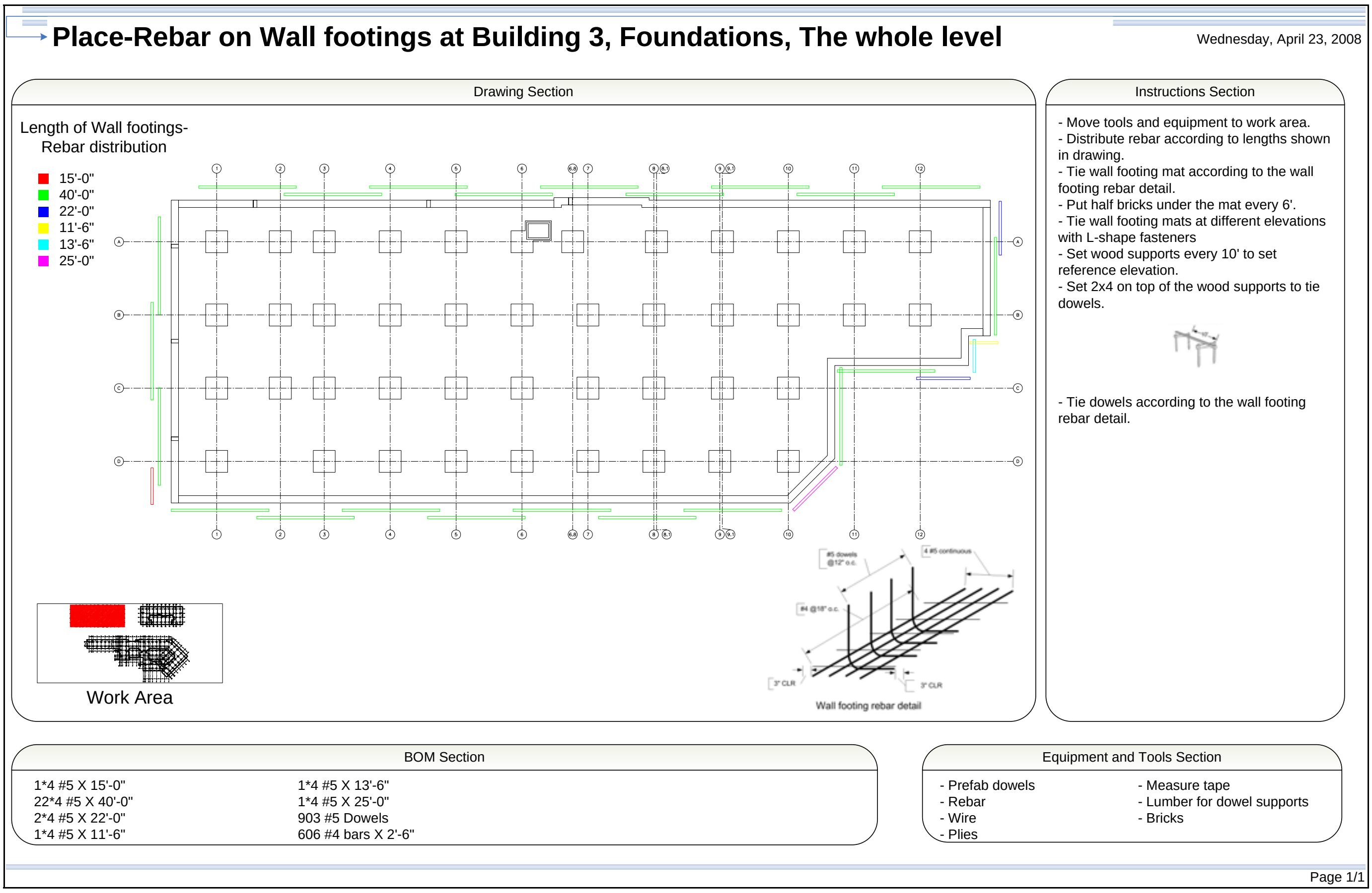
- Decisions made from design information contained in the product model (light-gray diamond shapes in Fig. 5). Examples: Is the BOF (bottom of footing) elevation constant? Is the wall higher than 8 feet?
- Decisions made from information provided by the user (dark-grey diamond shapes in Fig. 5). Examples: Are the L-shaped fasteners prefabricated? Is there a crane available?

The FIPAPM system customizes the selected process model by extracting the needed information from the product model and/or prompting the user to provide the needed information and answering the decision elements of the generic process model. This customization produces a custom path that contains a set of construction steps (rectangular shapes in Fig. 5) and equipment and tools (rectangular shapes with wavy bottom in Fig. 5) that apply to the specific conditions of the project. The information contained in this custom path populates the "instructions" and "equipment and tools" sections of the field instruction (Fig. 1).

The process model also contains best practices of the company about the content and format of the field instruction for that particular activity ("action-resource-object-work area" tuple). The best practices about this content and format are contained in the properties of the dark-grey and light-grey house shapes, respectively, of the process model. The content best practices define what building elements (e.g., walls, columns) from the product model will be included in the model view of the "drawing" section of the field instruction. The format best practices define the color coding to use for the included building elements and the type of view (e.g., plan, elevated, section, reflected, 3D) of the model view.

Finally, the process model also contains the best practices of the company about the materials that need to be quantified for the "bill of materials' section of the field instruction. This information is contained in the properties of the table-shaped element of the process model. These properties identify the materials that have to be quantified and the algorithm that relates these materials to building elements in the product model.

In both cases, the materials take-off and the contents of the model view, the respective building elements are constrained by the work area of the activity's work scope. Figure 6 shows a field instruction produced for the activity example.


Place-Rebar on Wall footings at Building 3, Foundations, The whole level

Wednesday, April 23, 2008

Drawing Section

Length of Wall footings-
Rebar distribution

🟥 15'-0"
🟩 40'-0"
🟦 22'-0"
🟨 11'-6"
🟦 13'-6"
🟪 25'-0"

Wall footing rebar detail

Work Area

Instructions Section

- Move tools and equipment to work area.
- Distribute rebar according to lengths shown in drawing.
- Tie wall footing mat according to the wall footing rebar detail.
- Put half bricks under the mat every 6'.
- Tie wall footing mats at different elevations with L-shape fasteners
- Set wood supports every 10' to set reference elevation.
- Set 2x4 on top of the wood supports to tie dowels.
- Tie dowels according to the wall footing rebar detail.

BOM Section

1*4 #5 X 15'-0"
22*4 #5 X 40'-0"
2*4 #5 X 22'-0"
1*4 #5 X 11'-6"
1*4 #5 X 13'-6"
1*4 #5 X 25'-0"
903 #5 Dowels
606 #4 bars X 2'-6"

Equipment and Tools Section

- Prefab dowels
- Rebar
- Wire
- Plies
- Measure tape
- Lumber for dowel supports
- Bricks

Page 1/1

Figure 6. Example of a field instruction for the activity example (Place-Rebar-Wall footings-Building 3, Foundations, The whole level).

4 IMPACTS

We evaluated the impact of the FIPAPM system with an experiment where the test subjects (17 graduate students) produced a good quality work instruction for the same activity using three methods.

- Base method: this method has neither a predefined procedure to produce work instructions nor a predefined format and content for the work instructions. This method represents the current state of practice.
- Manual FIPAPM: this method has both a predefined format and content for the work instructions (field instructions template) and a predefined procedure to produce those field instructions. The subjects follow the procedure manually which implies understanding each of the steps and the representations of the relevant information.
- FIPAPM prototype: this method is similar to the previous one but here the subjects use a software prototype so their understanding of each of the steps and the information representation is less relevant.

We compared the instructions produced by the subjects using each method based on three criteria.

- Effort: Total time (in minutes) to produce a work instruction. This duration includes looking for the information, doing calculations (e.g., quantity take-offs), and putting the information together.
- Correctness (error proneness): We analyzed three factors: 1) whether the instruction includes all the needed information, 2) whether the included information is correct, and 3) whether the included information is accessible (i.e., the user does not need to look for it somewhere else). Each factor is a yes/no evaluation so the correctness score ranges from 0 (totally incorrect) to 3 (totally correct). We assessed individually each type of information potentially included in the instructions (design, construction steps, equipment and tools, and quantities) and then averaged the results.
- Consistency: Inter-subject reliability analysis where we did pair-wise comparisons among the work instructions produced with the same method. This consistency analysis compared the format and content of the instructions for each type of information potentially included in the instruction (design, construction steps, equipment and tools, and quantities). The consistency score ranges from 0 (format: the information is shown very differently in each instruction; content: the instructions contain very different information) to 3 (format: the information is shown in the same format; content: both instructions contain the same information).

Figures 7, 8 and 9 show the results of these analyses.

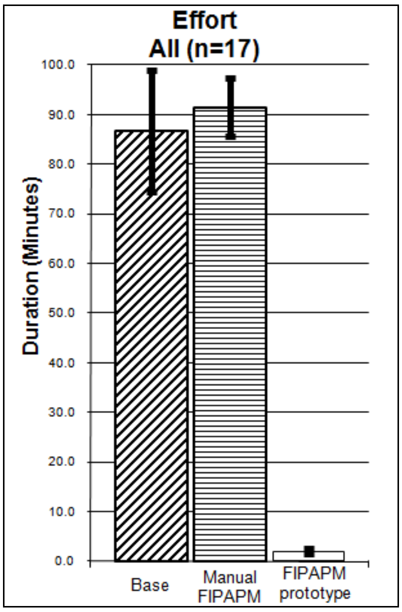


Figure 7. Results of the effort analysis.

The automated method is, of course, substantially faster than the other two methods. A more interesting result is that the base method requires (initially) less effort than the manual FIPAPM. This difference is due to the challenges of each method. The base method has the challenge of finding the information and defining the format/content for the instructions and the procedure to produce those instructions. There are no ambiguities involved since the subjects are following their own procedures. The FIPAPM system does not require defining everything and finding the information but it has the initial challenge of understanding the method (i.e., information schemas and steps). Language ambiguities and trade culture affect this understanding. The manual FIPAPM method also requires the subjects to use certain software tools (i.e., Autodesk Architectural Desktop and Microsoft Visio) which also present an initial challenge compared to the base method where the subjects could use anything they wanted (including sketches). This longer initial duration of the manual FIPAPM method illustrates why in absence of a computer interpretable method, the informal method will likely prevail over the formal method. We believe this duration difference would be even bigger for practitioners since we noted that trend for more experienced graduate students (small subset of the test subjects). We believe the bigger familiarity with practical knowledge of the more experienced subjects helps them to find information more quickly. We do not note differences between the test subjects for the other analyses. The speed results also show the larger time variability (standard deviation) of the base method compared with the manual FIPAPM method. This larger variability makes it difficult to manage the time of the field management personnel responsible of producing instructions using the base method.

The correctness analysis (Fig. 8) shows that the outputs of both FIPAPM methods (manual and prototype) are more correct and have smaller standard deviations than the outputs of the base method. The lesser correctness of the manual FIPAPM compared with the FIPAPM prototype can be explained, again, by the initial challenge of understanding the method.

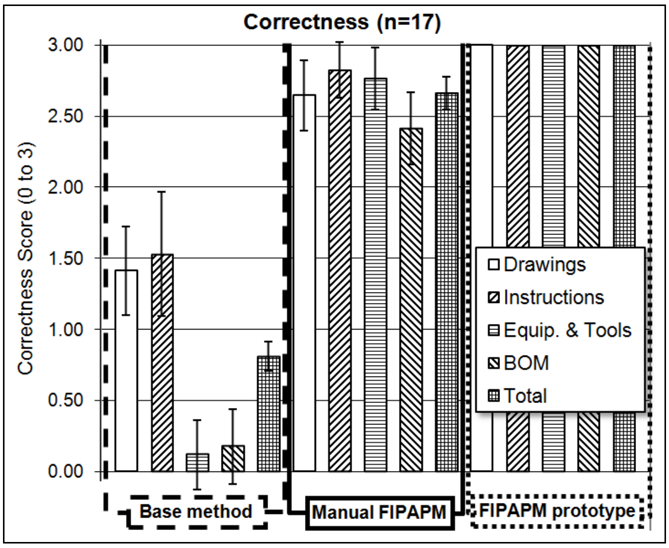


Figure 8. Results of the correctness analysis.

Finally, the consistency analysis (Fig. 9) shows that the consistency of the work instructions increases when we move from the base method to the manual FIPAPM method and finally to the FIPAPM prototype. An interesting result is the relatively high consistency of the equipment and tools and materials (BOM) content of instructions produced with the base method. However, the correctness graph (Fig. 8) shows that this type of content is highly incorrect for instructions produced with the base method. Therefore, the correct reading of Figure 9 is that this content (i.e., equipment and tools and materials) is consistently incorrect for the instructions produced with the base method. Figure 9 also shows that the instructions produced with the manual FIPAPM method have a format consistency that is higher than their content consistency. This difference exists because the field instructions template defines the format very clearly but the content still depends on the user's understanding of the FIPAPM method.

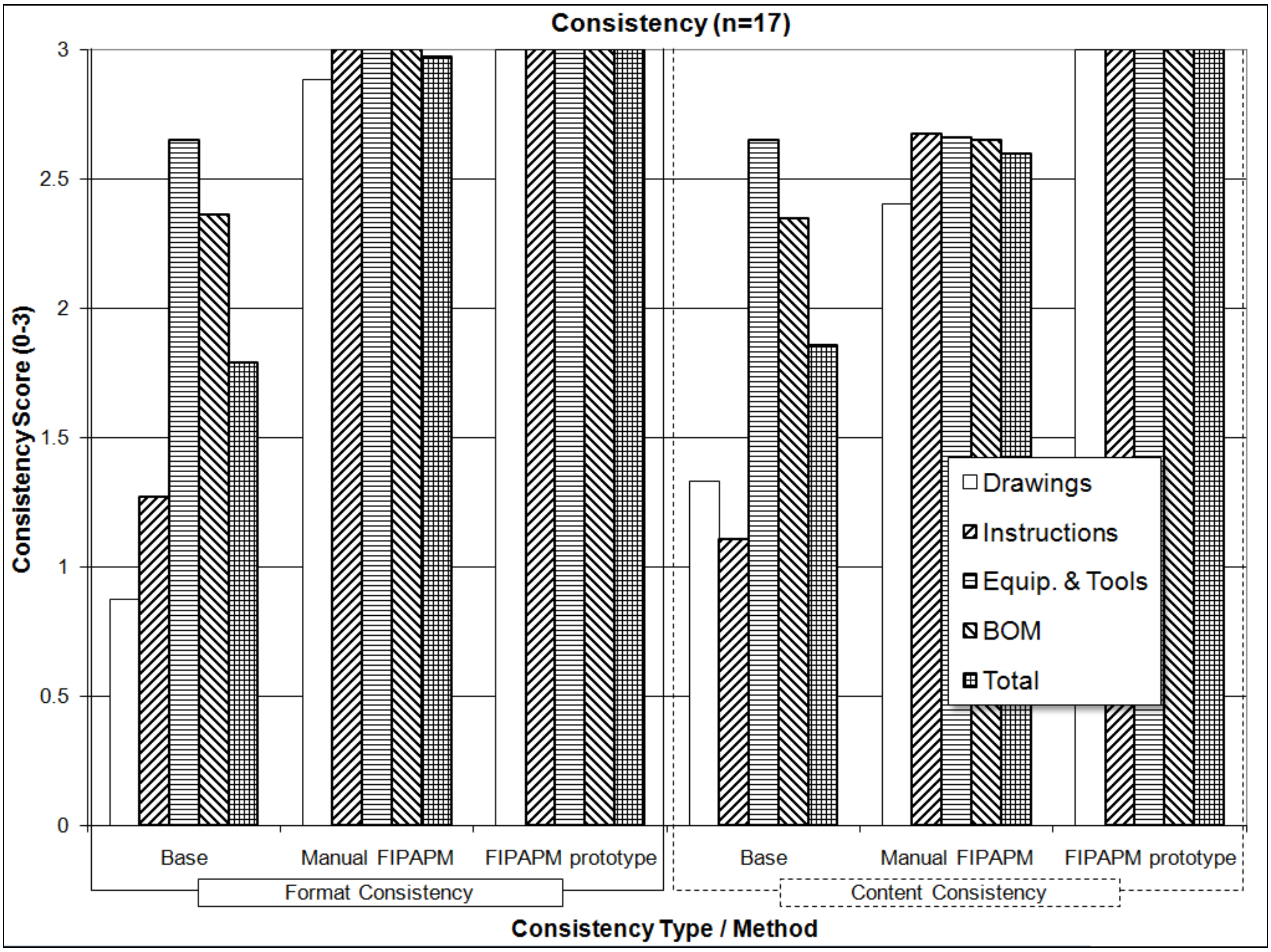


Figure 9. Results of the consistency analysis.

5 DISCUSSION AND FUTURE RESEARCH

The FIPAPM system proved to be faster, more correct and more consistent than the state-of-practice method to produce good quality work instructions. These results enable contractors to reduce the negative impacts produced by the use of informal verbal instructions.

The FIPAPM system uses an interesting approach of customizing generic process models with information contained in project-specific product models. This approach enables the standardization and reuse of construction knowledge, reducing the risk of knowledge loss inherent in the loss of experienced human resources.

The validation of the value of the FIPAPM system assumes the existence of a project's product model and company's process models. Although product models are being introduced in many construction projects, construction process models are still something rare in the construction industry. The authors recognize this challenge and believe that there is an important need for research to prove the benefits of and establish methodologies for creating and using this type of models in the construction industry. Our research proved the benefits of using construction process models for producing good-quality work instructions and it also found that these models could be used for new personnel training and construction process reengineering.

Our research focused on cast-in-place concrete construction in residential buildings so further research is necessary to extend the underlying information formalizations (schemas) so they can represent activity, product and process information for other construction disciplines and project types.

Addressing the limitation explained in the previous paragraph, the methodology behind the FIPAPM system could also be applied to more generic descriptions of work such as work method statements. In these statements, contractors have to either submit the work they will perform to be approved by the general contractor or they have to document what and how was done.

Another benefit of the FIPAPM system lies in the field instructions template. This template creates a written record of the design and construction information given to laborers. On the other hand, verbal instructions cannot be systematically retrieved in a later time and so they are a source for uncertainties and lack of accountability. Previous field instructions can be searched by building element, construction activity, work area, and, of course, date.

Finally, we developed the FIPAPM system as a means to deliver good quality information to laborers. Thus, this system does not allow collecting what happens in the field as laborers use the information given to them. We will conduct research to create bidirectional instructions that deliver information to laborers and also allow collecting information from them to keep the design and construction information updated as things change in the field.

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