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By

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METHOD TO PRODUCE FIELD INSTRUCTIONS FROM PRODUCT AND PROCESS MODELS FOR CAST-IN-PLACE CONCRETE OPERATIONS

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Abstract

The state-of-practice method to produce good and formal work instructions for construction laborers takes time, is error prone and produces outcomes with inconsistent format and content. That is why contractors rely on verbal work instructions in spite of the field mistakes and inefficiencies that this poor communication produces. Our research addresses the underlying scientific problem of this practical quandary: the lack of a formal method that defines the steps and information needed to produce good work instructions from a company's best practices and a project's 3D product model.

This paper describes an automated method (**F**ield **I**nstructions from **P**roduct **A**nd **P**rocess **M**odels, FIPAPM) to systematically produce work instructions with a predefined format and content (field instructions template) for cast-in-place (CIP) concrete operations using design and construction information contained in product and process models. The paper also explains the information schemas needed by the FIPAPM method to produce field instructions.

We developed this method and information schemas through active project participation and computer prototyping. Our validation of the FIPAPM method shows that it enables a faster, more correct and more consistent production of good work instructions than the state-of-practice method.

Keywords: Construction, product models, process models, work instructions, field information.

1. Introduction

Work instructions in the construction industry communicate design information (i.e., what and where) and construction information (i.e., how, who, and when) to laborers so they can perform the work necessary to build a construction project. These work instructions are traditionally delivered through informal, verbal explanations and the project's set of construction drawings. These verbal instructions are associated with mistakes and inefficiencies at the workface (Mourgues and Fischer, 2008). Some authors have presented more formal, written instructions to address the shortcomings of verbal instructions. Oglesby et al. (1989) describe the use of written instructions (what they call job-assignment sheets) as a good pre-planning practice. Mourgues and Fischer (2008) show that using what they call *field instructions* reduces rework and workface questions and increases productivity and safety compared with the traditional practice of verbal work instructions. Field instructions, in contrast to job-assignment sheets, are based on a template that defines the format and content of good work instructions. However, producing these types of instructions presents three main challenges.

1) **Effort**: it takes between 1 and 2 hours to produce a good, formal work instruction depending on the complexity of the instruction, availability and quality of the information (it could take much longer with poor or unavailable information), and the skills and knowledge of the person producing the instruction. Considering that a small contractor may perform daily, on average, three activities that require instructions, the total effort equates to 3 to 6 hours per day for the already overloaded field management personnel. Furthermore, the variability of this effort makes managing the time of the field management personnel difficult.
2) **Error risk**: integrating informally-described information from different sources (several drawings, company's best practices, quantity take-offs) presents a high risk of getting something wrong (e.g., using an out-of-date drawing, including a wrong detail, adding quantities that do not belong to the work scope).

3) **Inconsistency**: different people that produce field instructions will likely include different content and will present this content in a different format. This inconsistency hinders the quick understanding of the instructions and increases the laborers' resistance to use the instructions.

These challenges force contractors to rely on verbal communication and construction drawing sets for communicating work instructions. The key limitations that cause these challenges are the informal description of the information used to produce this type of instructions, the dependency on the construction knowledge of the producer of the instruction, and the lack of a clearly defined output and explicit mechanisms to produce that output. Therefore, there is a need for a methodology that addresses these limitations to reduce the above challenges for producing more formal and better quality work instructions.

This paper presents a method (FIPAPM) that addresses these challenges by extracting design and construction information from product (i.e., related with the facility), and process (i.e., related with the construction best practices) models and quickly, correctly and consistently producing field instructions (as defined by Mourgues and Fischer, 2008). This method relies on a formalization of the design and construction information that is needed to produce field instructions. We developed and validated this method within the cast-in-place (CIP) concrete domain. This method and related information schemas are the main contributions of this paper.

Section 2 explores the state-of-practice to produce work instructions and introduces our intuition (formalization of information involved in producing work instructions) to address the above challenges. Following this intuition, Section 3 describes existing information schemas and discusses their potential to allow the automated extraction of information useful to produce field instructions. Section 4 explains the FIPAPM method and the related information schemas. Section 5 describes the validation of this method and schemas. Finally, Section 6 summarizes the conclusions of this research.

2. State of practice for producing work instructions

Contractors normally communicate work instructions verbally and with references to construction drawing sets. However, some contractors produce higher quality work instructions as part of the work packaging process (Kim and Ibbs, 1995). In this context, we use work package from a production perspective as defined by Choo et al. (1999): “work package defines a definite amount of similar work to be done (or a set of tasks) often in a well-defined area, using specific design information, material, labor, and equipment, and with prerequisite work completed.” Figure 1 conceptualizes the approach these companies follow to produce work instructions.

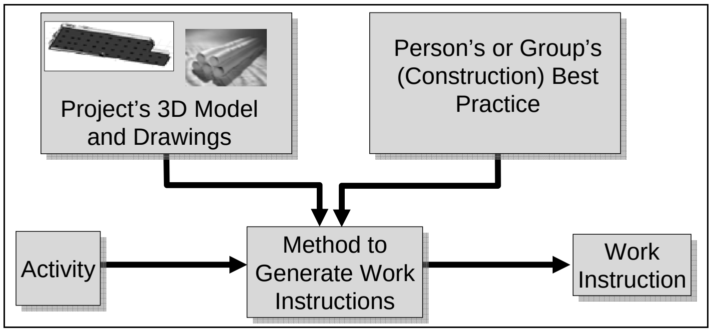


Figure 1. Conceptualization of current process to produce formal work instructions. A person or group produces a work instruction for a particular activity (e.g., dig footings) using design information obtained from the project’s 3D model, drawings and specification documents, and construction information (e.g., material, labor, equipment) obtained from that person’s or group’s best practices.

The three main actors in this approach are: design team, construction team, and laborers. The design team produces the project’s 3D model, drawings and specifications. The construction team could be only the superintendent, foreman or project engineer, or could be a group that includes consultants. This group produces work instructions based on its construction knowledge. Note that a company’s projects will likely have different construction groups and thus the respective construction knowledge will also be different. Finally, laborers are the work instruction users.

The approach shown in Figure 1 creates the challenges we explained in the previous section (i.e., effort, error-risk, and output inconsistency) because of the four limitations explained below.

- **Informal description of the activity and design information**: the informal activity description makes the work scope of the activity ambiguous. This ambiguity plus the informality of the design information that is dispersed in different sources (i.e., drawings, specifications, 3D models) increases the *chances of error* when producing a work instruction.
- **Dependency on construction information of the person or group that produces the instruction**: this dependency makes the content of the produced instruction *inconsistent* as this content varies every time a different person or group produces instructions.
- **Lack of the output definition:** this limitation increases the *output inconsistency* as the lack of a clear definition of the content and format of the work instruction to be produced makes this content and format even more dependent on the person or group producing the instruction.
- **Lack of definition of the steps in the method**: this lack of a predefined procedure to put together the needed information plus the informal description of all this input information (activity, design, and construction information) make it *time consuming* to produce work instructions.

At the same time, cultural and language differences between laborers and field management staff in industrialized countries and multinational projects make it very difficult for a person or group to create work instructions on a case-by-case basis that can address these cultural and language differences. For example, Spanish-speaking laborers have trouble understanding instructions produced by English-speaking superintendents. A method to produce work instructions that is less dependent on who is producing them (i.e., it is more consistent) can facilitate addressing these differences with a more structured approach.

On the other hand, today’s growing use of virtual design and construction (VDC) methods creates a big opportunity for using information contained in digital models. Fischer and Kunz (2004) define VDC as “the use of multidisciplinary performance models of design-construction projects, including the product (i.e., facilities), organization of the design-construction-operation team, and work processes, to support explicit and public business objectives.” In our case, product and process models can contain information valuable for producing work instructions. This means, our research can use multidisciplinary product models and process performance models to support business objectives – i.e., reduction of field mistakes and inefficiencies – of a given construction organization. However, the information in these models must be structured so it can be consistently interpreted and used.

Therefore, our intuition is that we can address the effort, error risk and consistency problems by formalizing the information involved in the process of producing instructions (Figure 2). This formalization will allow us to use product models as a source of design information and process models as a source of construction best practices to produce good work instructions. The use of best practices and the definition of the output will reduce the dependency on the producer of the instruction. We use the field instructions template to define the output because it is the only explicit definition of format and content for good work instructions in construction. This formalization of the input and output information enables an explicit definition of a method that can be automated.

The main challenge of the approach in Figure 2 is the lack of a method to leverage a project’s product model and a company’s construction best practices (in the form of process models) to produce field instructions. This challenge is about how to use best practices that include the scenarios that a company usually faces when executing construction work and select the particular scenario that applies to the particular conditions of the project represented by the product model. Section 4 explains how we addressed this challenge.

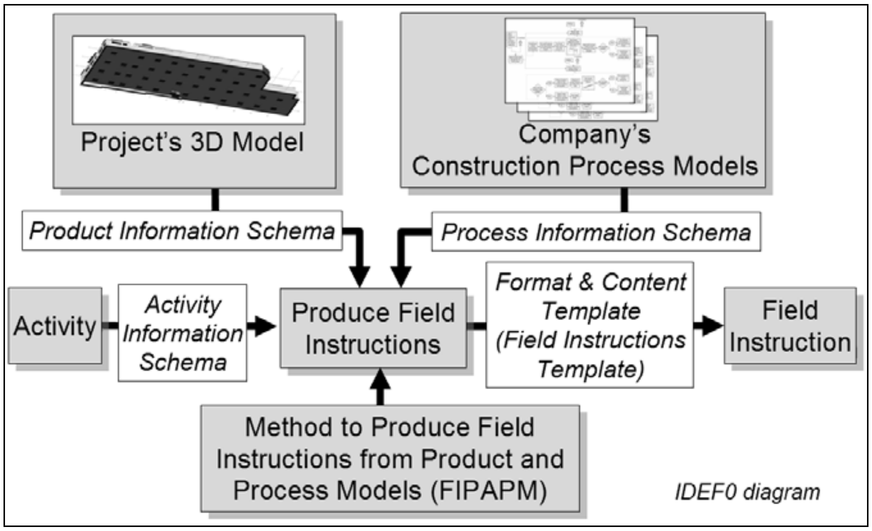


Figure 2. Intuition to address challenges of producing good work instructions. This intuition is based on the formalization of all the input and output information of the method.

Based on this intuition, we reviewed relevant literature about formalizations of the different input information. In other words, we built the FIPAPM method on literature about information schemas in each of the input areas in Figure 2: activity, product and process. We begin this review by defining the key concepts used throughout the paper to set up the vocabulary to discuss our literature review findings.

3. Activity, process and product information schemas

To assess the applicability of existing information schemas we considered whether the definition of information elements allows identifying the information related to the content and format of field instructions. The activity information schema must define a work scope that identifies the design and construction information needed to produce a field instruction. The product and process information schemas must enable the extraction of that design and construction information from the product and process models.

We found that the OAR (Object-Action-Resource) activity ontology (Darwiche et al., 1988) contains most of the information elements needed to define an activity's work scope for field instruction purposes. However, this ontology 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. 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 describe the building components of a work instruction.

Before discussing these information schemas in detail, we define the important concepts we use in this paper.

3.1. Concept definitions

Literature about construction digital models contains some ambiguities. Concepts such as product, process, and information models, ontologies and modeling languages are used, many times, interchangeably or at least loosely. We use the following definitions:

- **Product model**: we use this concept in the context of building projects so it refers to a digital representation of the constituent parts of a facility.
- **Process model**: we use this concept in the context of construction field operations so it refers to a graphic representation of field activities and resources, and their relationships (e.g., precedence, belonging). For example, a PERT diagram for a particular project.

- **Process modeling language**: symbols and their rules used to create a graphic description of a process (process model) (e.g., Flowchart, IDEF0, PERT). These symbols imply a certain data structure but do not describe the actual information model (see below) implicit in the process model.
- **Ontology, information model and information schema**: Ontology is a "specification of representational vocabulary for a shared domain of discourse" (Gruber, 1993). It contains a "vocabulary and the definition of concepts and their relationships for a given domain" (Spyns et al., 2002). On the other hand, an information model is a representation of data/information entities, their properties and their relationships for a particular application. These two concepts are similar but they differ in their level of generality (Spyns et al., 2002). An ontology is shared in the domain area (e.g., steel-structure cost estimating) for which it was developed while an information model is commonly used by only one computer application. So, when an information model is adopted as a standard, it becomes an ontology. Some standard construction information models (i.e., ontologies) are IFC (IAI, 2008) and gbXML (gbXML, 2008) while the formats used by commercial tools (e.g., ArchiCAD, Revit, Tekla) are examples of specific information models. We use the term information schema to refer to both ontologies and information models.
- **Information modeling language**: symbols and their rules used to create an information model (e.g., entity-relationship diagram, EXPRESS-G, NIAM, UML, IDEF1x).

Following, we discuss existing information schemas for construction activities, processes and products that we consider useful to extract design and construction information from product and process models and generate field instructions.

3.2. Activity information schemas

The purpose of the activity information schema in our intuition is to formally describe an activity's work scope as it relates to the content of the field instructions. Therefore, this schema needs to define what is happening, on what building element, and where in the project.

Darwiche et al. (1988) describe activities for an automated planning system using an Object-Action-Resource (OAR) ontology (adapted from Marshall et al., 1987) that identifies three key components of the work scope: 1) the object affected by the activity, 2) the action involved, and 3) the resources. Examples of a couple of activities using the OAR ontology are (using the Action-Object-Resource format): Paint-Wall-Ladder, Paint, Painter; and Weld-Mechanical Pipe-Welder. Note that there can be more than one resource such as in the first example. An important limitation of this ontology is that it lacks a description of the work area where the activity occurs. We do not know where the wall to be painted and the mechanical pipe to be welded are located.

Others have built on this ontology for different purposes. Aalami (1998) changed Object by Component and added Sequencing constraints to build the CARS ontology that enables the automatic generation of 4D production models. Staub-French et al. (2003) added Features to build the FOAR ontology that enables automatic cost calculations. However, the additions made by Aalami (1998) and Staub-French et al. (2003) do not help to locate the activity and do not directly affect the format and content of the field instructions for that activity.

Akinci et al. (2002) define space types involved in an activity but they do not present a description of the location of those spaces, they are linked to the 3D elements in a product model. Seppänen and Kenley (2005) state that, for typical building projects, the first three levels of a location breakdown structure (LBS) are: buildings or structurally independent parts of buildings; floors; and rooms, apartments or other spaces. Using these levels, it is possible to locate an activity in building projects.

Then, extending the OAR ontology with the three levels of LBS for building projects allows us to describe the building elements, resources and location of an activity that needs a work instruction.

3.3. Process information schemas

The purpose of this schema is to enable companies to describe a process that represents the best practices of the company to both perform a construction activity and communicate the field instruction (in terms of content and format) for that particular activity. The best practices and standard operating procedures (SOP) literature describes actual procedures for different processes (e.g., Davis and Kochhar, 2002; Lurey and Raisinghani, 2001; Hattemer-Apostel, 2001) but it does not identify the actual information entities or graphical language used in the description of those procedures. So, we focused on literature of existing information schemas with entities and properties relevant for our purpose and modeling languages that could describe those entities and properties. We found that IFC (IAI, 2008) and other information schemas contain some basic elements that are useful for our purpose but all of these schemas lack other very important information elements. We also found that basic flowcharting diagrams are a good modeling language to describe best practices to perform construction activities.

Many of the existing process information schemas (e.g., Karhu, 2001; El-Diraby and Zhang, 2006; Luiten and Tolman, 1997; Stumpf et al. 1996; Haymaker et al., 2004a) contain basic elements useful for our purpose such as activities, precedence relationships, and resources. Currently, the development of the IFC is the biggest effort for establishing an ontology for the AEC industry (IAI, 2008). IFC are a very big ontology that includes product and process entities, and we explored its application for our product (see next section) and process information schemas. IFC also include the basic process elements mentioned above. However, as in the cases above, IFC do not include entities and properties that would enable a formal, computer interpretable description either of the field instruction format and content for a particular activity or the multiple scenarios that affect the best practice to perform the activity.

Analogously, most process modeling languages represent the basic elements mentioned above within different contexts. Construction practitioners commonly use Gantt Charts and PERT diagrams to describe construction plans and schedules. On the other hand, construction researchers favor languages such as IDEF0 diagrams (e.g., Karhu et al., 1997; Laitinen, 1999; Kamara et al., 2000) to describe construction processes, and activity-cycle diagrams to describe construction processes in simulation languages such as STROBOSCOPE and CYCLONE (e.g., Martinez and Ioannou, 1999). These languages are easy to understand and good for their respective purposes but they cannot describe options of alternative sequences of construction steps that could happen based on project conditions such as water table elevation, soil capacity, wall heights, sustainability and safety considerations, building codes, etc. We found that the flowcharting language (ISO, 1985) includes decision elements that enable the description of these different construction scenarios. However, flowcharting and the other process modeling languages lack elements to describe the content and format of the field instruction related to a particular activity.

Then, flowcharting and its implicit information schema provide the base to represent best practices to perform a construction activity but we still need to add the information elements to represent field instructions format and content.

3.4. Product information schemas

The purpose of this schema is to identify building components in the product model to extract views and quantities of those components. For our research, these views can include tangible elements (e.g., walls, columns) and non-tangible elements (e.g., labels, dimensions). IFC (IAI, 2008) entities allow this identification but they do not identify non-tangible components in relation to tangible components (e.g., label of a particular wall). Thus, we can use IFC entities but we need to extend their scope to include non-tangible elements.

Summarizing our literature review, we found that the OAR ontology plus the 3 levels of LBS are useful to define our activity information schema; flowcharting diagrams allow representing construction scenarios and we can build on them to define our process information schema; and, finally, a broader definition of IFC entities supports our needs for the product information schema.

The next section explains how we used these points of departure to develop our information schemas and the method that uses those schemas to produce field instructions.

4. Method to Produce Field Instructions from Product and Process Models (FIPAPM)

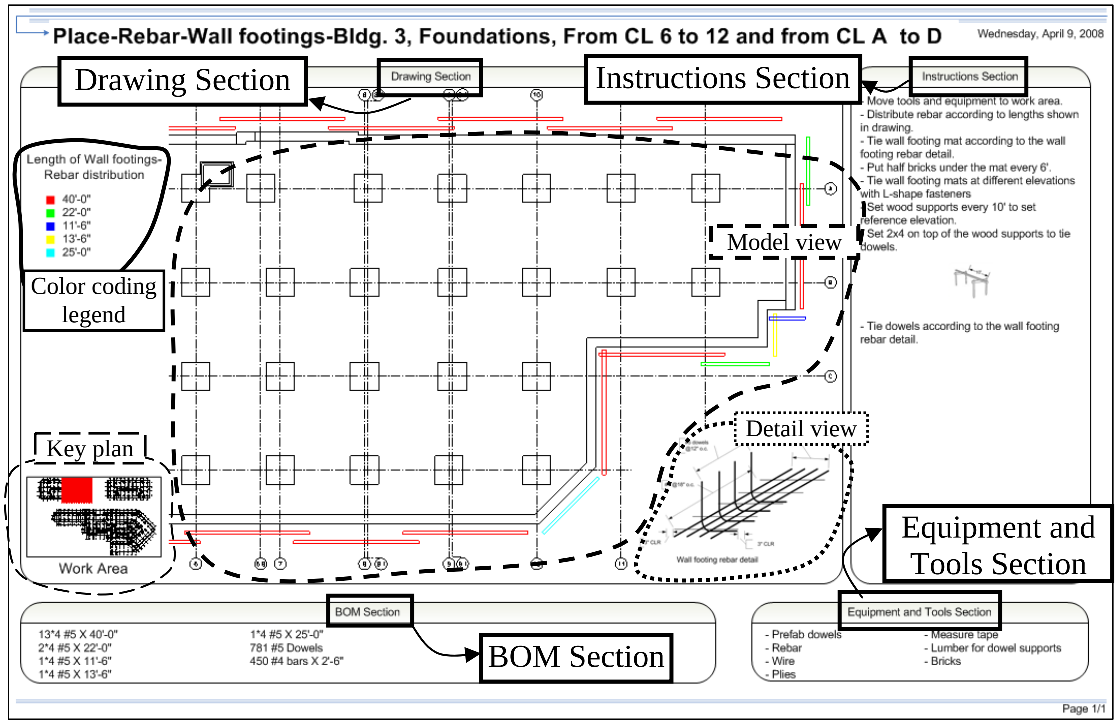
The FIPAPM method follows our intuition explained in section 2 and depicted in Figure 2. In contrast with the current state of practice shown in Figure 1, the information used by the FIPAPM method is formalized using information schemas. Thus, the user of the method can interpret the scope of an activity and correctly and consistently produce a work instruction for that activity based on a format and content template (field instructions template). To produce this instruction, the user interprets the design and construction information that controls this format and content.

Another difference with the current state of practice is in the actors of the process. The main actors in our approach are:

- **Field management (Foreman/Superintendent/Project engineer)**: user of the FIPAPM method. S/he produces a field instruction for each activity the laborers will work on.
- **Laborers**: users of the field instructions.
- **3D modelers**: producers of the 3D model and related construction information for the project. This model is done once at the beginning of the project and then updated during the construction phase.
- **Construction process experts**: mix of office and field experts that together agree on the company's best practices (represented by process models). The modeling of the company's best practices is done sporadically (e.g., every six months) as new methods, equipment, regulations, etc., become relevant.

The main difference regarding the actors is that the construction knowledge that controls the production of the instructions is not held only by the same person that produces the instruction (as it is in Figure 1) and, therefore, it does not change from project to project. In our approach, the construction knowledge used by FIPAPM is explicitly discussed and agreed by all the members of the expert group so the content and format of the instructions will not depend only on the particular person producing instructions for a project.

To understand the FIPAPM method, it is necessary first to understand its output, the Field Instructions Template. Figure 3 shows an example of a field instruction (i.e., work instruction that uses this template). We will use this example throughout this section to explain the information schemas and the FIPAPM method.



Place-Rebar-Wall footings-Bldg. 3, Foundations, From CL 6 to 12 and from CL A to D

Wednesday, April 9, 2008

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

13*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"
781 #5 Dowels
450 #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 3. Field instruction example. The figure highlights the instruction's four sections: drawings, instructions, equipment and tools, and BOM (bill of materials). It also highlights the four elements of the drawing section. The title of the instruction follows the AROW (Action-Resource-Object-Work area) schema explained below.

This template has four sections (a detailed description of the template can be found in Mourgues and Fischer, 2008):

- **Drawing section**: Design information, i.e., locations, dimensions, materials, etc. This section is composed of four elements: a color coded model view (the use of color allows conveying more information), detail view, color coding legend (that explains the color used in the model view), and key plan (work area).
- **Instructions section**: Construction steps and special considerations that laborers must follow to perform the work described by the field instruction.
- **Equipment and tools section**: Equipment and tools needed to perform the work described in the field instruction.

- **Bill of materials (BOM) section**: Materials and their quantities needed for the work included in the field instruction.

For the given activity, the FIPAPM method selects the data it needs from the 3D product model and the process model corresponding to the company's best construction practices for the activity, extracts the information from that selection, and organizes it in the four sections of the field instructions template. Figure 4 shows a high level description of the steps followed in this method.

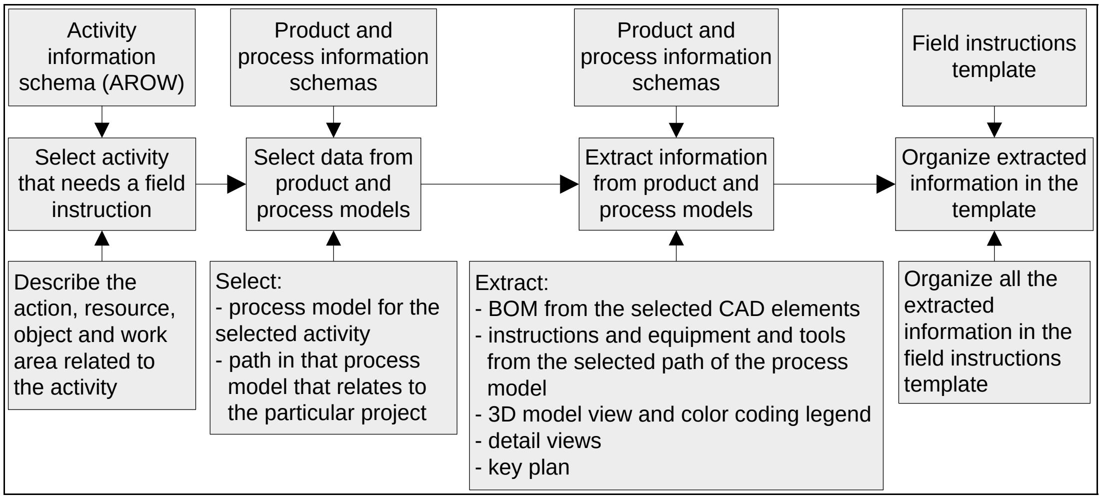


Figure 4. High level description of the steps of the FIPAPM method. The top boxes indicate the information schemas used in each step (middle boxes) while the bottom boxes give more detail about each step. The key contribution of this method is the formalization of the use of product and process models which we explain in section 4.4.

The different information schemas (activity, product and process) must allow the selection, extraction and organization of the information elements as shown in Figure 4. We will explain the information schemas based on these steps and the field instruction example in Figure 3.

4.1. AROW, activity information schema

The purpose of this information schema is to describe the work scope of the activity that needs a field instruction. The AROW schema results from the synthesis of the OAR ontology (Darwiche et al., 1988) and the three levels of LBS in typical building projects (Seppänen and Kenley, 2005). AROW describes an **A**ction that happens on a **R**esource of an **O**bject in a specific **W**ork area. AROW uses “Resource” differently than OAR. AROW’s Resource refers to a material that will be part of (e.g., concrete, rebar) or give shape to (e.g., formwork) a building element (i.e., Object). OAR’s Resource refers to any resource needed for that activity (e.g., labor, equipment, material, information, etc.). This difference relates to the information needed to produce a field instruction. Field instructions support the work of a specific crew so labor information is not needed by the FIPAPM method, and equipment and other technical information is included in the process models (see section 4.3). Table 1 exemplifies the use of the AROW information schema to describe the work scope of four activities.

We specify the Object (or component) using two entities: Element and Subgroup. Element specifies the building component such as walls, columns, slabs on grade, wall footings, etc. Subgroup indicates a subset of a building component such as a type of column or slab (e.g., patio, corridor). This subgroup-building component relation is similar to a work breakdown structure (WBS) where the immediately inferior level of a product element such as a column describes subgroups of that product element such as the different types of columns. Object and Resource are closely related but the entities are not interchangeable as Resources (e.g., rebar, formwork) cannot be Objects (e.g., wall) but they will always either be part of an object (e.g., rebar of a wall) or give shape to an object (e.g., formwork of a wall). This means that the role of Resource is to identify a subcomponent of the Object.

Table 1. AROW examples. Activity 2 corresponds to the example in Figure 3. These descriptions can be interpreted by a computer and then used to extract information from the product and process models.

AROW		Examples			
		Activity 1	**Activity 2**	**Activity 3**	**Activity 4**
Action		Pour	Place	Set	Place
Resource		Concrete	Rebar	Forms	Wire mesh and vapor barrier
Object	Element	Walls	Wall footings	Columns	Slab on grade
	Subgroup	All	All	Type A	All
Work Area	Building	Garage	Building 3	Terminal B1	Building A
	Level	4th floor	Foundations	2nd floor	Ground
	Zone	The whole level	From CL 6 to 12 and from CL A to D	From local coordinates 0’,0’ to 25’,40’	Pour 2

We specify the Work Area using three entities: Building, Level, and Zone. These entities come from the 3 levels of LBS for typical building projects (i.e., building, floors, and spaces). “Building” denotes an area of the project such as building X or terminal Z. “Level” specifies a level of the project area defined by “Building” (e.g., 3rd floor of building X). We changed “floors” to “levels” to include areas that “floors” cannot describe (e.g., different levels of a slab-on-grade within the same building floor). “Zone” describes a particular region of the level defined by “Level.” We changed “spaces” to “zones” because our entity is similar to the ifcZone entity. The FIPAPM user can specify “Zones” with one of the four methods described below.

- **Column Lines**: using column lines as a reference system, the FIPAPM user can specify a particular zone within a building level (e.g., activity 2 in Table 1).

Furthermore, the FIPAPM user can apply a buffer (i.e., linear extension) to extend the zone a certain distance out of the boundary defined by the column lines.

- **Construction Zone**: certain construction methods define zones such as concrete pours on a post-tensioned slab. An example is activity 4 in Table 1.
- **Arbitrary Area**: the work area in the field is defined, many times, by practical limitations (e.g., blocked access, unfinished previous work, and equipment capacity) which imply that the zone does not match any reference element (column lines or construction zones). In these cases, the FIPAPM user can define an arbitrary area as the zone by using an arbitrary coordinate system (e.g., project local coordinates, product model coordinates). An example is activity 3 in Table 1.
- **Whole Level**: this zone includes the whole level of the building specified by the entities Building and Level. An example is activity 1 in Table 1.

4.2. Product information schema

The purpose of this schema is to describe building elements so the FIPAPM method can identify the elements and extract quantities and views of these elements from the product model as described in Figure 4. This identification and extraction is based on the activity previously selected so there is a clear relationship between the activity and product information schemas. Table 2 describes and exemplifies the entities and properties of the product information schema and their relationship with the AROW schema.

The examples shown in table 2 are not fixed values. These values depend on the construction discipline (e.g., cast-in-place concrete, wood framing, plumbing, etc.) and a company’s needs, culture and preferences. However, the users of the FIPAPM method must be consistent in the values they use across the company.

Table 2. Description of entities and properties of the product information schema and their relationship with the AROW schema. The first example for each property (in bold) corresponds to the example in Figure 3 with the exemption of the construction zone. This exemption is because the example in Figure 3 does not use the "construction zone" method to specify the "zone" of the activity's work area.

Entity	Properties	Examples	Relationship with AROW
Building component	Building Element	**Wall footings**, columns, beams, slabs on grade.	Object-Element
	Element Material	**Rebar**, concrete, forms, wire mesh, gravel.	Resource
	Element Subgroup	**All**, Type B2, Balcony.	Object-Subgroup
Work area	Project Area	**Building 3**, Garage Y, Terminal Z	Building
	Area Level	**Foundations**, Ground, 1st floor.	Level
	Construction Zone	Pour 3, 1st group	Zone (only for construction zone method)

The properties of our product information schema are related with high level IFC entities. This relationship is important as many commercial CAD platforms are becoming IFC compatible. Below, we describe this relationship.

- **"Building Element" property**: relates to the ifcBuildingElement entity. This IFC entity is a super type of ifcBeam, ifcColumn, ifcWall, etc. Our building element property has the same type of values but it is not restricted to a particular list of values. Another difference is that "building element" not only refers to tangible things but also to conceptual elements such as layout grids.

- **“Element Material” property**: relates to the ifcMaterial entity. An important difference is that this property, similarly to “building element”, also includes annotations such as dimension labels of a particular element or labels that show a specific property value of that element in the 3D model.
- **“Project Area”, “Area Level”, and “Construction Zone” properties**: similar to ifcBuilding, ifcBuildingStorey, and ifcZone entities respectively.

IFC do not have an entity similar to “Subgroup” but the ifcBuildingElement’s property “grouping” enables defining the same type of relationship between “Building Element” and “Subgroup”. This property allows ifcBuildingElement being part of a logical group of objects.

An important difference between the product and activity information schemas is that the “object-element” and “resource” entities of the activity information schema only refer to information of tangible building elements such as walls and concrete respectively. As mentioned above, the related entities of the product information schema (building element and element material) can also refer to conceptual elements such as layout grids and annotations respectively. This difference means that the values used for “object-element” and “resource” will be a subset of the values of “building element” and “element material” respectively.

Regarding the level of detail in the product model, the granularity (i.e., size) of the building elements must be consistent with the definition of the work area, which has to be consistent with the work practices of the company. This means that if the contractor usually pours walls in lengths of no more than 75’ because of formwork constraints, the size of the building element “walls” must allow to define a work area of that length. This consistency requirement is similar to the situation in 4D modeling or BIM-enabled quantity take-offs.

4.3. Process information schema

The purpose of this schema is to describe a process that represents the best practices of a company to both perform a construction activity and communicate the field instruction for that particular activity. Best practices to perform an activity will vary depending on project situations such as soil conditions, building codes, sustainability considerations, weather, etc. Thus, to make the process model project-independent and therefore applicable to the whole company, we found that the process models must include alternative scenarios for the construction process based on the situations that a contractor normally faces. When creating a field instruction, the user of the FIPAPM method customizes this generic model (i.e., selects the proper scenarios) according to the project conditions ("select path" in Figure 4). On the other hand, best practices to communicate a field instruction are project-independent so they do not need to be part of the different construction scenarios. These communication best practices must specify all the building elements of the model view of the field instruction (see Figure 3), their respective color coding, and the material quantities.

Below, we explain this schema's entities and their properties. Then, Figure 5 illustrates the process modeling language we defined to create process models based on this schema, and Figure 6 exemplifies the use of this language with the process model used to create the example field instruction in Figure 3.

- **Process model**: Set of construction steps, decisions, and equipment and tool elements organized by precedence. The process model describes a company's best practice to perform a certain construction activity (e.g., set forms on walls, place rebar for columns). It also includes the model view content, model view format and BOM entities (explained below) needed for that particular construction activity. The only property of the entity "process model" is its name which is based on the tuple Action-Resource-Object (as defined by the AROW schema;

e.g., place-rebar-wall footings in Figure 6). This name format enables the selection of a process model based on a selected activity (Figure 4).

- **Construction Step**: Describes a particular step in the process of performing the construction activity described by the process model. This entity has 4 properties:
  - Step: description of what to do (text in the rectangular shapes, Figures 5 and 6).
  - Equipment and tools: list of the equipment and tools needed to do that step (text in the rectangular shapes with curved bottom, Figures 5 and 6).
  - Visual aid: step illustration (image inside the rectangular shape, Figure 6).
  - Detail view: name of an illustration referenced by that step. This information, not graphically shown by the process model, provides a reference to the detail view element of the drawing section of the field instruction (see Figure 3).
- **Decision from user information**: Condition that offers two options (Yes/No) to include alternative scenarios that depend on information that must be provided by the user of the FIPAPM method (e.g., current conditions of the soil, access to the work area, use of a particular equipment, etc.). These are the dark diamond shapes in Figures 5 and 6.
- **Decision from 3D model information**: Condition that offers two options (Yes/No) to include alternative scenarios that depend on information that is contained in the 3D digital model (e.g., wall width, column height, changes in slab elevation, etc.). These are the clear diamond shapes in Figures 5 and 6. This entity has eight properties that allow the automatic evaluation of the 3D model to make the decision (i.e., Yes/No) during the customization of the process model.
  - Condition type: specifies whether the condition is *evaluative* (i.e., the yes or no decision depends on the value of a property of a building component) or *comparative* (i.e., the decision depends on the comparison between properties of a building component and a benchmarking building component)
  - Building component: specifies the building component that will be used for the evaluative or comparative condition. This component is specified by the three properties of the building component entity of the product information schema

(i.e., building element-element material-element subgroup), enabling the automatic checking of this condition in the 3D model.

  - Property of building component: specifies what property of the building component will be used for the evaluative or comparative condition.
  - Value type: since there will likely be multiple instances of the building component in the work area defined by the activity, the “value type” specifies whether all the values, the average or any value must comply with the condition to make it true.
  - Conditional operator: specifies the type of evaluation or comparison (e.g., greater than, equal, less than).
  - Value: for the evaluative conditions, this property specifies the value to which the property of the building component is assessed using the conditional operator. When the value is empty for an evaluative condition, the assessment is reflective, i.e., assessed against itself (see example below).
  - Benchmarking building component: for comparative conditions, this property specifies the building component that will be used for the comparison.
  - Property of benchmarking building component: for comparative conditions, this property specifies the property of the benchmarking building component that will be used for comparison.

  The values of these properties for the example in Figure 6 (i.e., is BOF (bottom of the footing) constant?) are: condition type (evaluative), building component (wall footings-concrete-all), property of building component (bottom elevation), value type (all values), conditional operator (equal). Therefore, for this condition to be true (i.e., Yes decision), all the values of the bottom elevation of the “wall footings-concrete-all” elements must be equal.

- **Model View Content**: Description of the building components that will be shown in the drawing section (model view) of the field instruction for the particular construction activity described in the process model. This entity is the black/white house shape in Figures 5 and 6. This entity uses the 3 properties of the building component entity of the product information schema (i.e., building element-

element material-element subgroup) so the FIPAPM user can select the proper CAD components in the 3D model. This list of building components is project-independent as it follows the contractor's standards about the content that the model view should include. For example, the building components specified in the process model in Figure 6 are: wall footings-concrete-all, column footings-concrete-all, PT (post-tensioned) footings-concrete-all, wall footings-rebar distribution-all, column layout grid. However, there are no PT footings in the actual field instruction shown in Figure 3 (based on the process model of Figure 6) as the project did not have that building component.

- **Model View Format**: Description of the type of view (e.g., floor plan, elevation, section, 3D) that will be used to show the model view content and the criteria for color coding this content. This entity is the gray house shape in Figures 5 and 6, and has one property that identifies the view type and the six properties below (for each building component in the "model view content") that define the color coding criteria.
    - Criteria type: specifies whether the criterion is *evaluative* – i.e., the color coding depends on the assessment of the value of a property using a conditional operator and a target value –, *comparative* – i.e., the color coding depends on the comparison between a property of a building component and a property of a benchmarking building component –, or *explorative* – i.e., every value of the building component's property is colored differently.
    - Property of building component: specifies what property of the building component will be used for the color coding criterion.
    - Conditional operator: specifies the type of evaluation or comparison (e.g., greater than, equal, less than).
    - Value: this property is used only for evaluative criteria similarly to the case of decisions from 3D model information.
    - Benchmarking building component: analogous to decisions from 3D model information.

  - Property of benchmarking building component: analogous to decisions from 3D model information.

  In the example in Figure 6 (and depicted in Figure 3), only one building component was color coded (wall footings-rebar distribution-all). The values of the above properties for that building component are: criteria type (explorative), property of building component (length).

- **BOM (Bill of Materials)**: Description of the content of the bill of materials section in the field instruction for the construction activity described in the process model. This entity is represented by the table shape in Figures 5 and 6 and uses four properties – three properties that identify building components (building element, element material, and element subgroup) and "quantity" – to identify a quantity take-off algorithm. The user of the FIPAPM method uses this algorithm to take off the quantities from the 3D model for the BOM section in the field instruction. Our research scope did not include a review of existing quantity take-off methods and their benefits/problems, but we developed a custom solution where we defined – at the project level – algorithms that relate material items not necessarily included in the 3D model (such as dowels and #5 rebars) with the building components (using the three properties of the building component entity of the product information schema). These material items populate the BOM section in the field instruction.

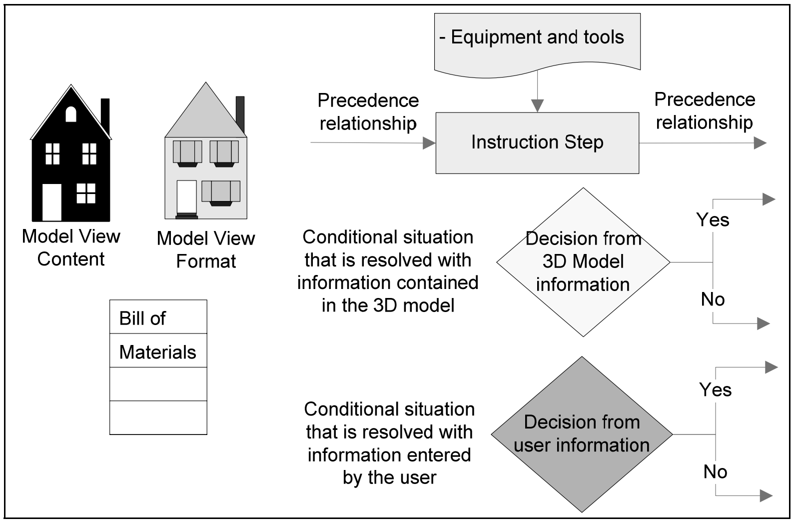


Figure 5. Process modeling language based on our process information schema. This diagram illustrates the symbols used to describe a construction field process.

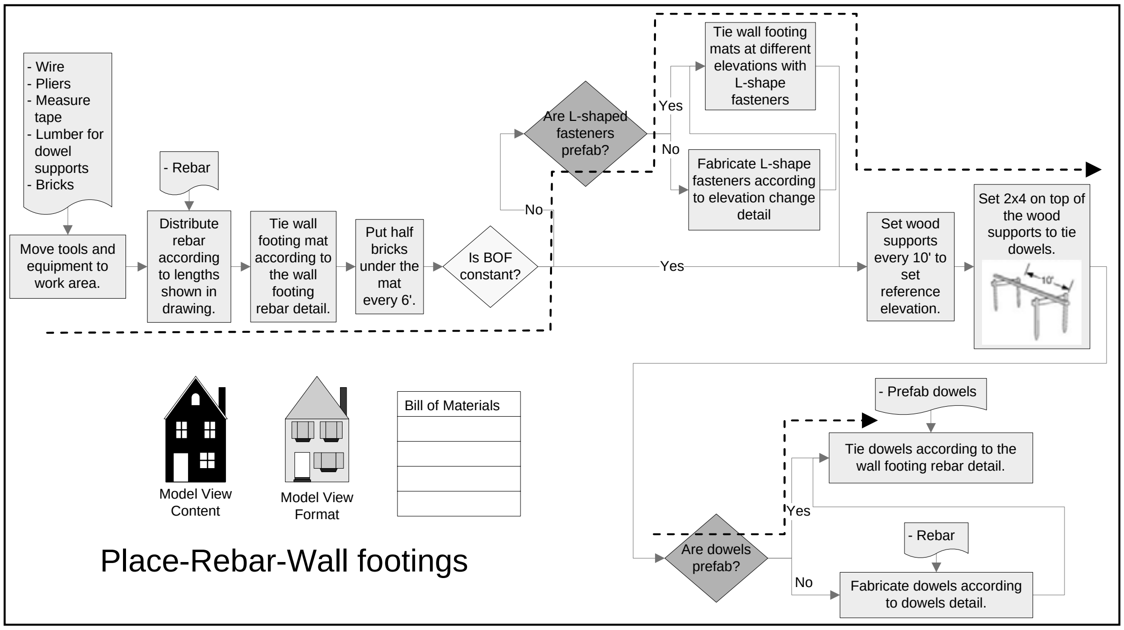


Figure 6. Example of construction process model. This model shows several alternatives of construction steps. For example, if the BOF (bottom of footings) changes in elevation ("no" alternative in the model), the process includes the use of L-shaped fasteners that may or may not be prefabricated. The segmented lines are not part of the model but are annotations to show the custom path for the example in Figure 3.

We pointed out during the explanations above how the three information schemas relate to each other to enable the steps of the FIPAPM method. Figure 7 depicts the field instruction information model using an entity-relationship diagram that contains all the entities, properties, and relationships previously explained.

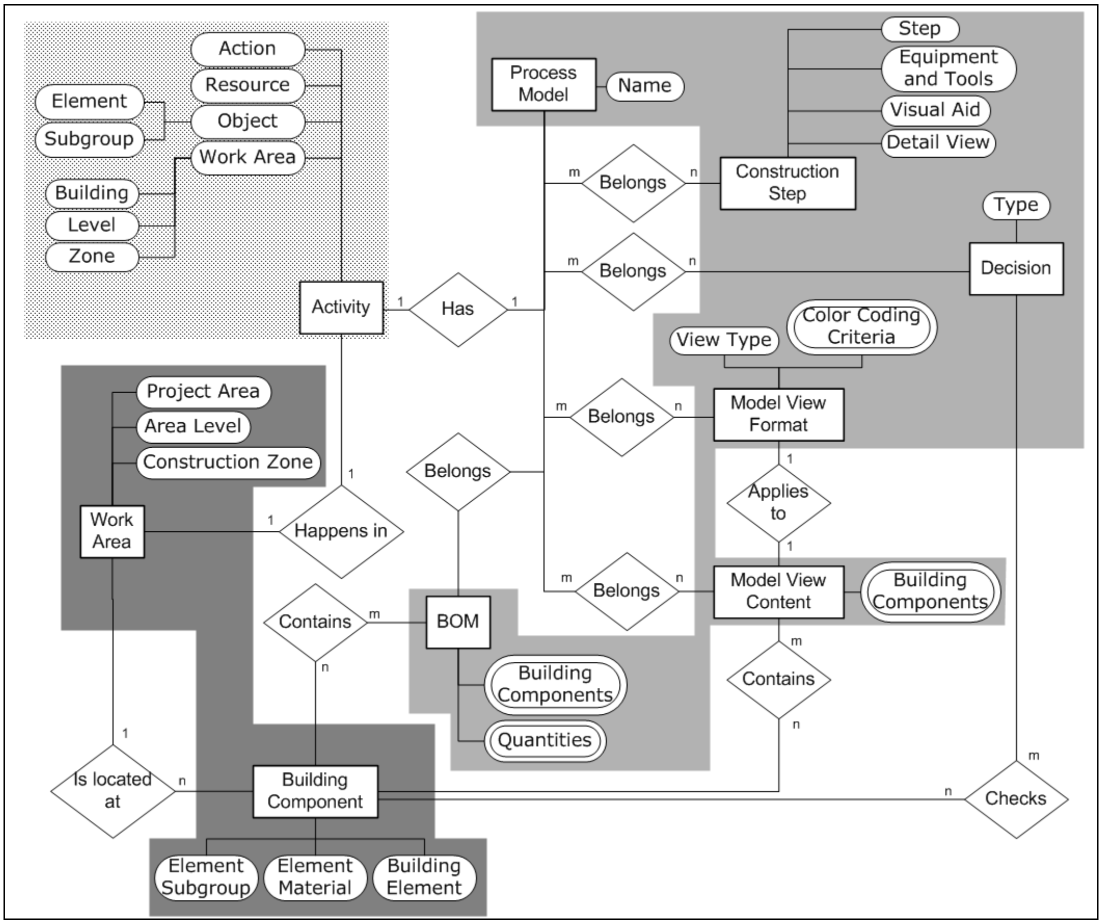


Figure 7. Field instruction information model for the FIPAPM method. Each gray background identifies the entities and properties that belong to the product (darkest gray), process (medium gray), and activity (lightest gray) information schemas.

4.4. Steps of the FIPAPM method

Figure 8 details the steps of the FIPAPM method and the use of the different information schemas that were summarized in Figure 4. The steps shown in Figure 8 correspond to the items in the bottom boxes in Figure 4.

Following, we explain each FIPAPM step that the user of the FIPAPM method (i.e., project engineer, superintendent or foreman) follows to produce a field instruction. The explanations reference the information schemas explained previously and connect to the example in Figure 3.

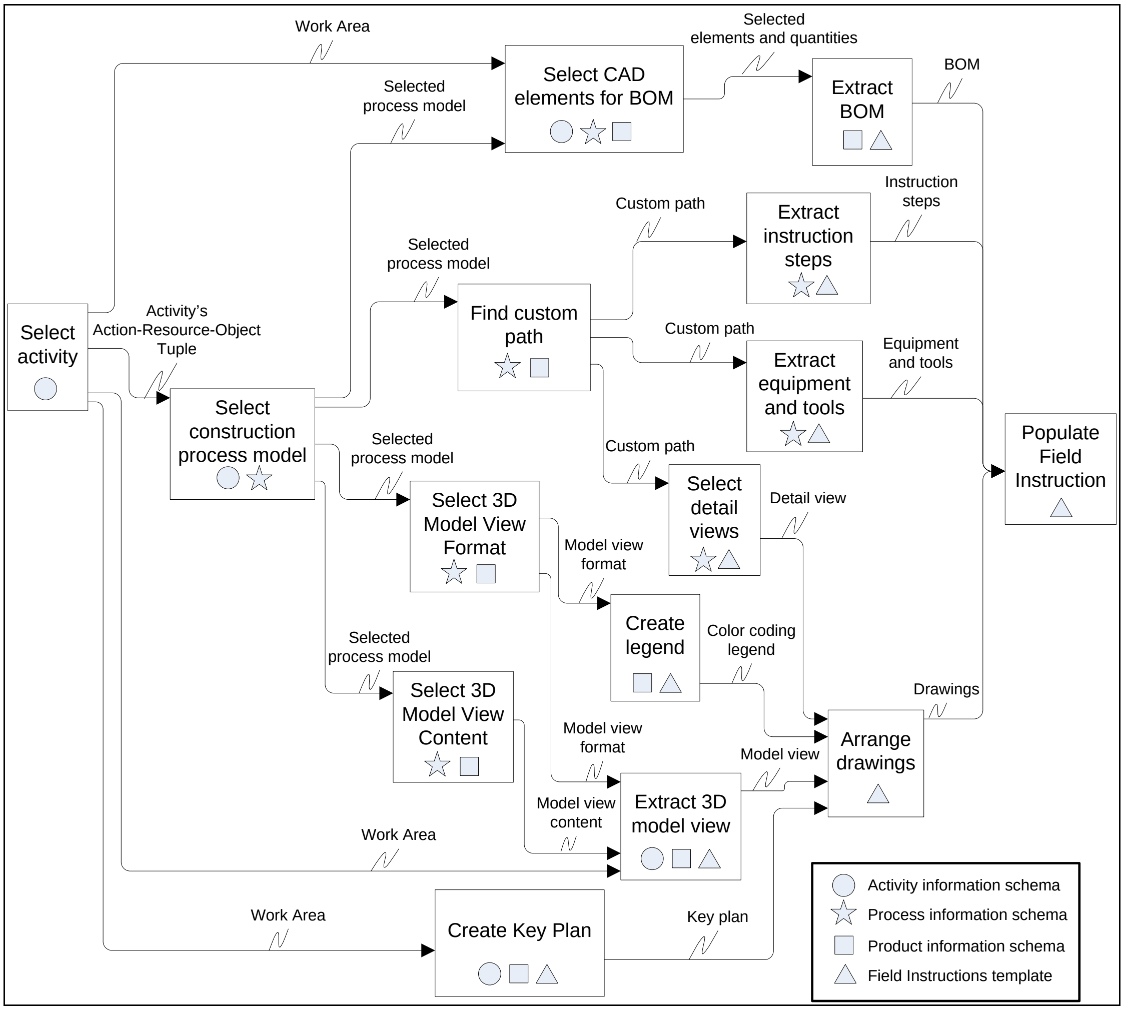


Figure 8. Sequence of FIPAPM steps and information schemas. Note that several steps of the method use more than one information schema. In those cases, the user of the FIPAPM method uses the relations between the different information schemas depicted in Figure 7.

- **Select activity**: Based on the project schedule and site conditions, define an activity for which laborers need a field instruction. To describe the activity, use the

AROW (Action-Resource-Object-Work Area) activity information schema (see section 4.1).

Example in Figure 3: select the activity Place (action) Rebar (resource) of the Wall footings (object) in bldg. 3 (work area-bldg), foundations (work area-level), from column lines 6 to 12 and A to D (work area-zone).

- **Select construction process model**: Select the process model that represents the best construction practices of the company to perform the selected activity. This selection consists of matching the action-resource-object part of the AROW schema with the name of the construction process model based on the process information schema (see section 4.3).

  Example in Figure 3: select the process model Place (action) Rebar (resource) of Wall footings (object)
- **Select CAD elements for BOM**: Select the CAD elements from which the material quantities will be extracted. An entity of the process information schema (BOM entity) defines the quantity take-off algorithm. This algorithm identifies the building components based on the company's best practices. The work area part of the activity information schema defines the subset of building components that will be used for the BOM.

  Example in Figure 3: in the selected process model, the BOM entity defines the algorithm "wall footings-rebar distribution-count". This text is the name of the algorithm that the user has to apply.
- **Extract BOM**: Take off the quantities of the selected CAD elements and prepare the bill of materials.

  Example in Figure 3: Use the algorithm definition to count the number of reinforcement bars based on the number of CAD elements previously selected.
- **Find custom path**: Each construction process model includes several potential scenarios (e.g., for different soil types, wall heights, water table elevation) that affect the construction activity represented by the process model. Thus, the process model can incorporate most of the situations contractors usually face in the field. When producing field instructions for a particular project, the user has to

customize the selected process model for the specific conditions of the project. This customization consists of solving the decision elements throughout the process model (see section 4.3) and yields a custom path, i.e., the set of step and equipment and tool elements that apply to the particular conditions of the project. *Example in Figure 3: First answer, Is the BOF (bottom of footings) constant (in elevation)? The answer in our example is "No". Then, following the process map, answer, Are the L-shaped fasteners prefabricated? The answer is "Yes". Finally, Are the dowels prefabricated? The answer is "Yes". These answers produce the custom path shown in Figure 6.*

- **Extract instruction steps:** Once the process model is customized, there is a unique sequence of construction steps (i.e., custom path) that represents the construction activity to be performed. The FIPAPM method user extracts the description of those construction steps from the process model.
  Example in Figure 3: Extract the text of the following steps in Figure 6: Move tools…, Distribute rebar…, Tie wall footing mat…, Put half bricks…, Tie wall footing mats…, Set wood supports…, Set 2x4 on top…, Tie dowels according…
- **Extract equipment and tools:** Extract equipment and tool information from the custom path that was previously selected.
  Example in Figure 3: Extract the text of the following equipment and tools in Figure 6: Wire, Pliers, Measure tape…, Rebar, Prefab dowels
- **Select detail views:** Extract the name of the detail views from the custom path. Each instruction step can reference the name of a detail view that applies to that step. The FIPAPM user checks each step in the custom path for these references.
  Example in Figure 3: Extract the detail name: "Wall_footing_rebar".
- **Select 3D model view content**: Select the content (i.e., the CAD elements) of the model view that will be extracted from the 3D model. The FIPAPM user looks for this content information in the "model view content" entity of the process information schema based on the company's best practices.

Example in Figure 3: the "model view content" entity identifies the following elements: wall footings-concrete, column footings-concrete, PT footings concrete, wall footings-rebar distribution, and column layout grid.

- **Select 3D model view format:** Select the format (i.e., color coding criteria and view type) of the model view that will be extracted from the 3D model. The "model view format" entity defines this format based on the company's best practices.

  Example in Figure 3: the "model view format" entity identifies a plan view that color codes the "wall footings-rebar distribution" based on its length following an explorative approach, i.e., each length has a different color. The other content of the view is not color coded (i.e., it is black).
- **Extract 3D model view**: Extract a view from the 3D model based on the model view content and format defined by the respective entities in the process model.

  Example in Figure 3: create a plan view showing the CAD elements identified above and color code them as indicated above.
- **Create legend:** Create a legend that explains the color coding criteria used in the model view based on the definition of the entity "model view format".

  Example in Figure 3: create a table showing the colors used for each length of the CAD elements "wall footings-rebar distribution" and the length value for each color.
- **Create key plan:** Create a key plan that shows a plan view of the entire project highlighting the work area defined by the activity.

  Example in Figure 3: create plan view of the entire project (3 buildings) and highlight building 3 from column lines 6 to 12 and A to D.
- **Arrange drawings**: Manually lay out the model view, detail view, key plan, and legend in the drawing section of the field instructions template. The layout must ensure clarity of all the information.
- **Populate field instruction:** Place all the pieces of information already obtained (i.e., drawings, BOM, instruction steps and equipment and tools) in the respective sections of the field instructions template.

The explicit definition of the information model shown in Figure 7 and the detailed steps explained above allows the automation of the FIPAPM method. We did a computer prototype implementation as part of our validation methodology. We used property sets in Autodesk Architectural Desktop to implement the product information schema and Microsoft Visio to implement the process modeling language with the underlying information schema in the shapes' custom properties. We automated the FIPAPM methodology using the Express Edition of Microsoft Visual Basic.

As the explanations above show, FIPAPM integrates product and process information. The next section discusses the interaction of these information types in FIPAPM and the differences with this interaction in other methods.

4.5. Product and process information interaction

The FIPAPM method integrates product and process information in two ways:

- The entity "decision from 3D model information" from the process models evaluates conditions in the product model to solve the decision. This decision entity identifies building components using the three properties of the building component entity of the product information schema (i.e., building element, element material, and element subgroup), and applies conditions to particular properties of those building components.
- Entities in the process model – model view format, model view content, and BOM entities – identify building components and quantities in the product model that will be part of the model view and BOM section in the field instruction

Other methodologies also integrate product and process information. Below we discuss the similarities and differences of the interactions in the FIPAPM method with methodologies that deal with similar information.

4D models link activities of a process model (i.e., schedule) with building components in a product model so these components can be animated over the time to visually analyze construction sequences. These schedule activities are similar to the activities for which field instructions are produced. However, FIPAPM does not link these activities to building components. FIPAPM links are at a higher level of detail since the interactions explained above occur between information elements of the process model that describes that activity and the building elements.

Resource-constrained schedules (Brucker et al., 1999) link quantities from building components in a product model with activities in a schedule. This interaction is similar to the interaction in FIPAPM between the “bill of materials” entity of the process model and the building elements in the product model. Since there is only one “bill of materials” entity in the process model that represents the best practices of an activity, the interaction is directly between the activity and the group of building elements that are used to extract the bill of materials, similarly to the resource-constrained schedules.

Narratives (Haymaker et al., 2004b) describe design processes that include entities that reference any kind of information – including product and process information – but without directly linking to particular information entities (such as building components).

In manufacturing, concurrent product and process design (Cutkotsky and Tenenbaum, 1990) integrates the design of a product with the design of the process to produce that product. This approach informally links product and process information as their interactions are implicit and do not identify specific information entities and their relationships as the FIPAPM method.

CAD/CAM integration (Xu and He, 2004) links the geometry information (product) with the manufacturing operations (process) to materialize the design. This interaction is much more detailed than the interactions in the FIPAPM method as the controlled manufacturing environment and the very well defined manufacturing operations (e.g., drill, cut, weld) allows a direct relationship between the geometry and the operation type and parameters (e.g., direction of drilling, depth of cut).

In conclusion, the interactions between product and process information in the FIPAPM method occur at an intermediate level of detail: higher than 4D modeling but lower than CAD/CAM integration.

5. Method and information schemas validation

The FIPAPM validation looks for evidence of a reduction in the challenges of the state-of-practice method to produce good work instructions. Thus, we validated the FIPAPM method and related information schemas asking a group of 17 civil engineering students to produce work instructions for a CIP concrete activity using three methods without time limit.

- **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 information schemas.
- **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 schemas is less relevant.

We then compared the output of each of these methods based on the metrics we identified as the main causes why companies do not currently produce good and formal work instructions: required effort, error proneness, and output inconsistency (see section 1). Table 3 describes how we measured each validation criterion.

Table 3. Description of measurements used for each validation criterion.

Criteria	**Measurements**
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).

The experiment purposively exposed the subjects to the methods with a very short training. Thus, the results do not include the learning curve effect giving, therefore, an indication of the initial challenges of using the methods. These challenges relate with technological and methodological barriers, i.e., with the technologies (mainly the software) used by the subjects for each method and with the method itself. We performed the validation test in two instances: one had 10 students at an advanced stage in their studies (old students) while the other instance had 7 students at an earlier stage (new students).

The effort analysis (Figure 9) shows that the automated method is, of course, substantially faster than the other two methods for the two groups of students. A more interesting result is that the base method requires (initially) less effort than the manual FIPAPM does for the old students. 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. FIPAPM 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. Interestingly, in the case of the new students, the effect of the method challenges was counteracted by the students' lack of knowledge and confidence about the construction methods and drawings which increased the time they took using the base method. The new students continued working on the base method until they saw their peers were finishing. The surprisingly small standard deviation shows that peer comparison effect. The speed result for all the students (graph at the right in Figure 9) also shows 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. This finding validates the observation in the field mentioned at the beginning of the paper.

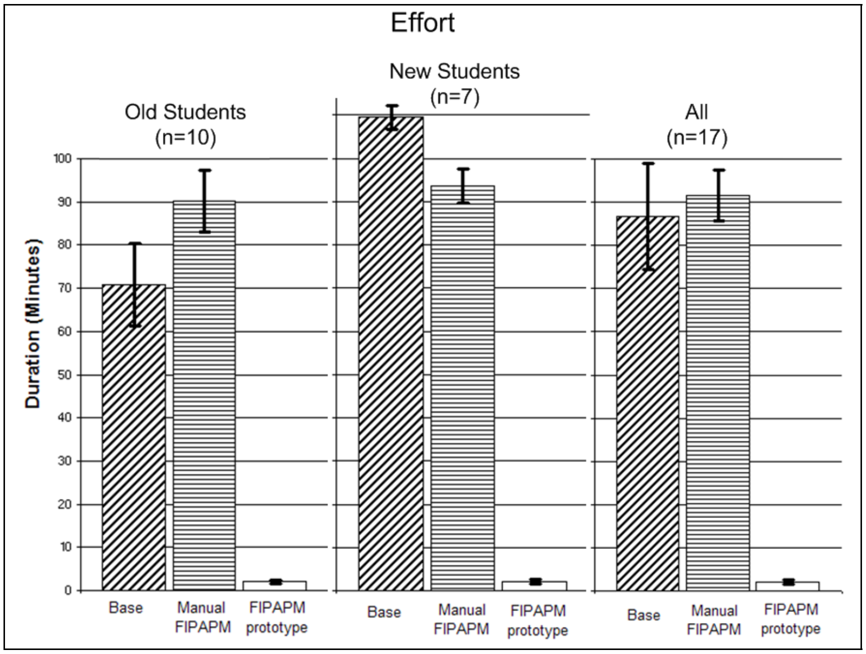


Figure 9. Results of the effort analysis. The three graphs show that the FIPAPM prototype enables a much faster generation of instructions than any of the other methods for both old and new students. The base method is faster than the manual FIPAPM for the old students while it was the opposite for the new students. The vertical lines on top of each bar show the standard deviation.

The correctness analysis (Figure 10) 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.

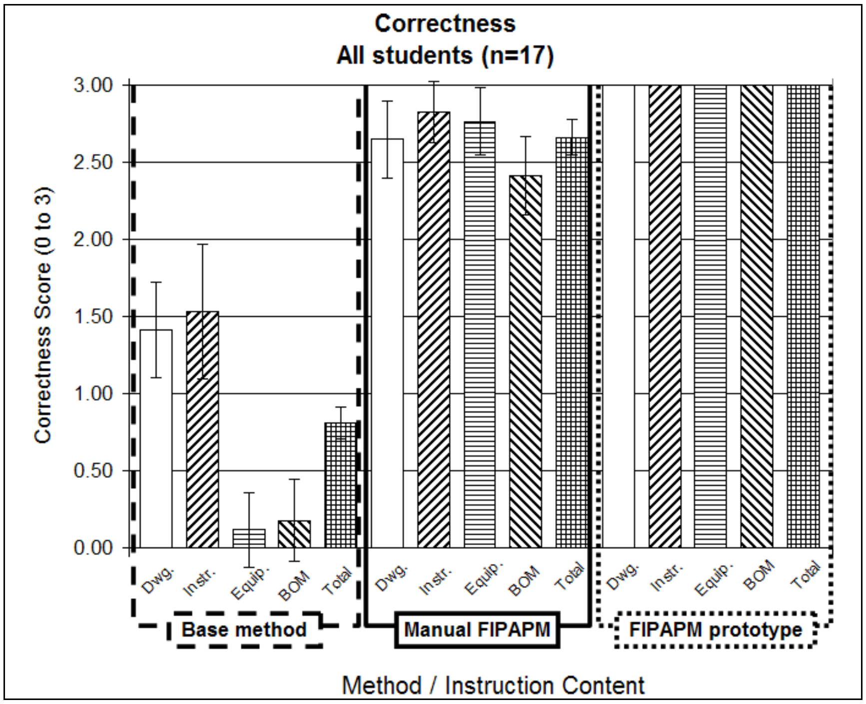


Figure 10. Results of the correctness analysis. The graph shows that both FIPAPM methods (manual and prototype) produce more correct instructions than the base method and with smaller variability (standard deviations).

Finally, the consistency analysis (Figure 11) shows that the consistency of the work instructions increases when we move from the base method to the manual FIPAPM method and finally 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 (Figure 10) shows that this type of content is highly incorrect for instructions produced with the base method. Therefore, the correct reading of Figure 11 is that this content (i.e., equipment and tools and materials) is consistently incorrect for the instructions produced with the base method. Figure 11 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.

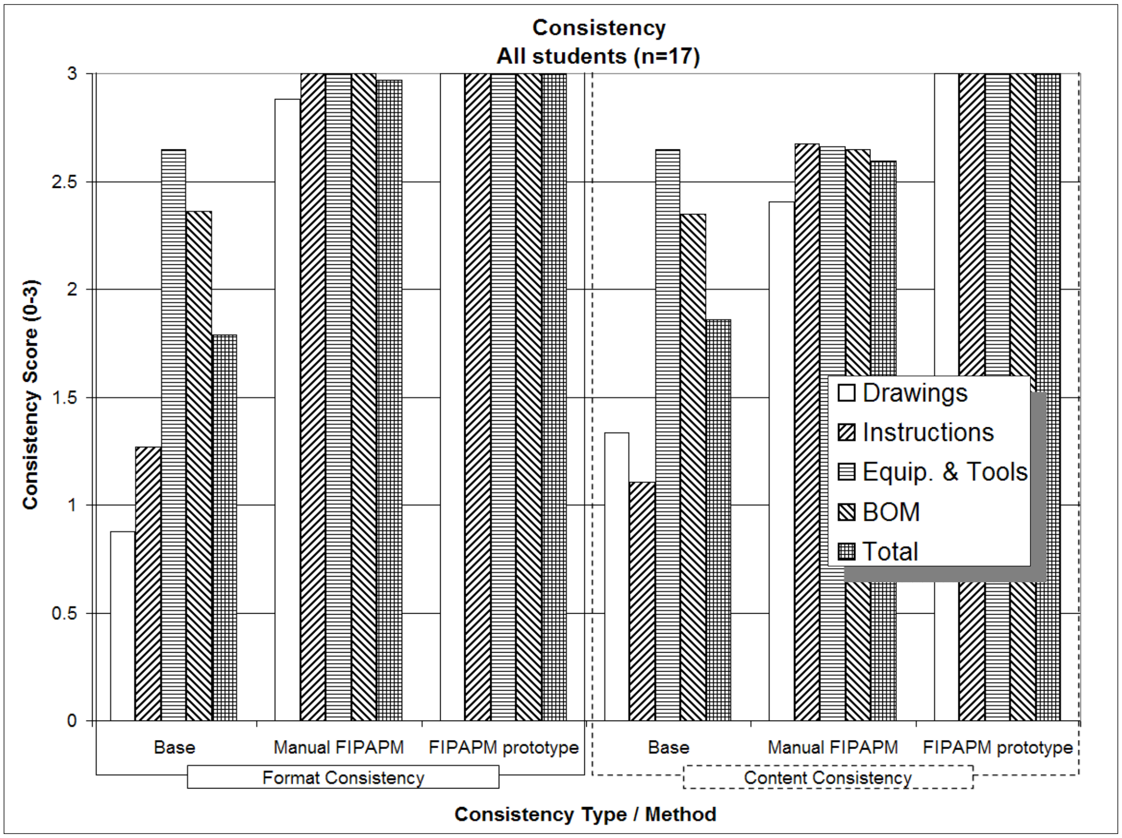


Figure 11. Results of consistency analysis. The graph shows that both FIPAPM methods are more consistent than the base method.

6. Conclusions

The effort needed to produce good work instructions, the chances of error inherent in this process, and the inconsistency of its outputs force construction contractors to rely on the verbal communication of work instructions to their laborers, triggering many field mistakes and inefficiencies. We presented a method (FIPAPM), and its related information schemas, to produce field instructions (i.e., work instructions based on the field instructions template) that address the challenges of producing good work instructions. The FIPAPM method takes advantage of the opportunities presented by VDC methods by using information contained in product and process models.

Based on the validation discussed in the previous section, we claim that the FIPAPM methodology reduces the problems of effort, error risk and inconsistency when compared with the current state of practice. This reduction will enable contractors to produce formal and better quality work instructions that will reduce field mistakes and inefficiencies.

We discuss below the specific contributions of this paper, their relations with the relevant literature, and their limitations. At the end, we suggest future research enabled by this research.

6.1. FIPAPM method

The existing literature does not provide a formal method to produce work instructions so, based on the validation explained above, we claim that the FIPAPM method is a contribution to the domain of CIP concrete construction. This contribution has the following limitations:

- The method was developed based on the field instructions template that is currently validated only for the domain of CIP concrete operations. Thus, the contributions presented in this paper are also limited to this domain. We plan to extend this method to other trades (e.g., plumbing, framing, etc.).
- The quantity take-off mechanism implemented in the FIPAPM method is not comprehensive as take-off methods were out of the scope of our research. The implemented method can relate a material quantity to only one building component (e.g., number of dowels relate to the length of the wall footings) so, currently, more complex relations cannot be used.
- The content of the product model (building components included in the model) has to be consistent with the best practices defined in the process model for the FIPAPM method to work. In the example used through the paper, the process model specified a color coding for the model view based on the building element

"Wall footings-Rebar distribution" (Object-Resource). So, the product model has to include elements that represent the rebar of the wall footings in a temporary position based on the construction practice (described in the process model): laborers distribute rebar at the side of the wall footings before placing it in its final position. This limitation makes it necessary for the contractor to ensure product and process models are consistent. A product modeling guideline based on the best construction practices of the company (described in the process models) will reduce this limitation.

6.2. AROW activity information schema

We extended the OAR activity ontology (Darwiche et al., 1988) into AROW to add another level of detail to the Object definition that allows specifying a subgroup of objects. Our extension of OAR also adds a Work Area definition based on the three levels of LBS for typical building projects (Seppänen and Kenley, 2005) to specify the location where the activity happens. This contribution has the following limitations:

- The work area element is based on the three levels of LBS of typical building projects: buildings, floors, and spaces. Civil and industrial projects may need other properties to define a work area so our information schema may not be suitable to describe locations in these project types. We plan to extend the work area definition to include other project types and other construction trades.
- This schema defines information entities (i.e., action, object, resource, and work area) but it does not specify the values for these entities. For example, the schema does not specify if a particular resource should be called "rebar" or "reinforcement steel". The schema leaves that up to the contractor. However, this requires that the different actors of the FIPAPM method (i.e., field management, laborers, 3D modelers, and construction process experts) agree on the values they will use for each information entity throughout the company.

6.3. Process information schema

We used flowcharting (ISO, 1985) as the base for the process modeling language and the underlying information schema that describes the field construction processes for the work instructions domain. We used three basic flowcharting elements: processing steps (rectangles), decisions (diamonds), and documents (rectangle with wavy bottom). We customized these elements for construction field processes so processing steps are construction instruction steps, decisions can be decisions from user information or decisions from product model information, and documents are the process' equipment and tools. We also added information entities specific for the work instructions: model view content, model view format, and bill of materials.

Our process modeling language is an important contribution to knowledge as it allows describing multiple scenarios of construction field processes. We implemented the mechanism to automatically customize these generic processes for the specifics of a project. We validated this claim together with the validation of the FIPAPM method as the students had to customize the construction process we use in the experiment. This contribution has the following limitation:

- The mechanism to solve decisions from product model information was validated in the domain of CIP concrete construction. Other construction disciplines may need different mechanisms to check conditions in the 3D model to evaluate these decisions. We plan to extend this mechanism to other disciplines in the future.

We speculate that our process modeling language has also a big practical significance as it allows companies to describe their best practices and use them not only for the purpose explained in this paper but also for general training, process reengineering, and knowledge management.

6.4. Product information schema

The six information elements that define this schema are based on five IFC (IAI, 2008) entities: ifcBuildingElement, ifcMaterial, ifcBuilding, ifcBuildingStorey, and ifcZone. The other information element is based on the grouping property of ifcBuildingElement. Our schema contributes to the knowledge by specifying what information entities and properties are needed to produce field instructions. This contribution has the following limitation:

- The work area entity of our product information schema, similarly to the work area of the AROW schema, is based on the three levels of LBS for typical building projects. Therefore, it is limited to building projects.

6.5. Suggested future research

We suggest future research to overcome some of the limitations stated above. Specifically, we suggest:

- Extend the FIPAPM method to other construction disciplines: future research should evaluate differences between CIP concrete and other disciplines and generalize the presented research to address these differences instead of developing different templates and information schemas for each discipline.
- Extend the work area definition to include other project types (civil and industrial projects).

Also, we suggest studying the strategies and challenges of implementing the FIPAPM method in a contractor organization.

This future research will extend the application domain of the FIPAPM method and facilitate its implementation.

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