INTRODUCTION

A number of information systems, such as ERP systems (Wagner & Monk, 2008) and business process management (BPM) systems (Chang, 2005; WfMC, 1999), have been developed to automate business processes. Those information systems employ a variety of process modeling languages, including BPMN (OMG, 2010a), EPC (Scheer, 1999), IDEF3 (Mayer et al., 1995), UML activity diagrams (Ambler, 2004; OMG, 2010b), and Workflow Management Coalition (WfMC) standards (WfMC, 1999).

These modeling languages represent business activities and their ordering relationships as control-flow process models. Activities are called tasks in BPMN, functions in EPC, units of behavior in IDEF3, and actions in UML. Typical ordering relationships include sequence (e.g., voting after discussing), AND for concurrency (e.g., scheduling production and purchasing production materials separately and concurrently), XOR for exclusive (exactly one) choices (e.g., approving or disapproving an application), and OR for inclusive (at least one) choices (e.g., interviewing one or more of suspect, victim, and witness separately and concurrently). To study the common syntactic and semantic features of process modeling languages, Figure 1 gives examples of control-flow process models represented in five different modeling languages. Appendix A...
provides a comparison of those modeling languages by using them to represent the same process. The process structures in the process models in Figure 1 will be used in discussions throughout this paper.

Because a formal semantics of control-flow process models is needed for process modeling, verification, and automation in information systems, substantial research efforts have been made on specifying a formal semantics of control-flow process models for more than a decade (Chen & Scheer, 1994; Dehnert & van der Aalst, 2004; Dumas, Grosskopf, Hettel, & Wynn, 2007; Kindler, 2006; Langner, Schneider, & Wehler, 1998; Mendling & van der Aalst, 2006, 2007; Rittgen, 2000; van der Aalst, 1998, 1999; van der Aalst & ter Hofstede, 2005; Wynn, Edmond, van der Aalst, & ter Hofstede, 2005). However, there is still lack of well-accepted formal semantics of control-flow process models for two reasons. First, when modeling languages like BPMN, EPC, IDEF3, UML, and WFMC standards are developed, their informal semantics are typically described using examples, but their formal semantics are not defined. Second, although a number of formal semantics have been proposed, the existing semantics specifications have limitations in terms of accuracy and completeness. Those limitations will be discussed in detail later.

To address this research problem, the objective of this paper is to propose a more accurate and complete formal semantics for control-flow process models than the existing semantics specifications. To accomplish this research objective, we will provide an in-depth review of the existing semantics specifications, propose a new formal semantics for control-flow process models, and provide a comparison to show the desirable features that are supported by this new semantics but not by the existing semantics specifications. We will also discuss possible extensions of this new semantics.

**EXISTING WORKS ON THE SEMANTICS OF CONTROL-FLOW PROCESS MODELS**

Before proposing a new formal semantics, the existing semantics specifications must be evaluated to justify whether the proposal of a
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