Multi-Level Simulation of Digital PSPs

I-Jong Lin and Jun Zeng; Hewlett Packard Laboratories; Palo Alto, CA, USA

Abstract

As Print Service Providers (PSPs) become more digital and move toward digital presses and digital workflows, a technique from Electronic Design Automation called multi-level simulation can simultaneous analyze and recreate interplay of operations, document design, and lean manufacturing with the next generation of PSPs. Multi-level simulation recognizes that hierarchical design has different levels of abstraction and each layer of abstraction has its own design language to search its respective design space. However, multi-level simulation integrates these multiple heterogeneous and overlapping layers of design abstraction for an optimal system goal. This goal for silicon chip is power, clock speed, or die size; the goal for a digital PSP is, ultimately, operational efficiency in the face of variability of job fulfillment. Multi-level simulation of a PSP bind together the competing goals of manufacturing efficiency, operational overhead, and content fulfillment capabilities; we submit there are three abstraction layers for these PSP goals: job for routing both inter-PSP and intra-PSP, PDL transformations for workflow, and image for visual inspection. Using Ptolemy EDA tools as a backbone, we will demonstrate this approach on such complex, high-value digital workflows such as security documents and automated print quality analysis, in terms of higher operational efficiency and profit per pages.

Introduction

This paper talks about the concept of using a well-known technique called *multi-level simulation* to give insight into the end-to-end costs of running a PSP in an efficient manner. Multi-level simulation manages the analysis of a system like a PSP in the face of both complex system internal interactions and heterogeneity of processing components. We will apply this technique in order to handle specific type of PSP where IT infrastructure is closely integrated with physical manufacturing infrastructure.

We use multi-level simulation environment to capture both the physical and digital processing of a PSP in a single functional representation, and model its end-to-end system behavior. This type of simulation recognizes the physical and digital domains and their boundaries, and allows design space exploration and optimization between both domains. The choice of domain for the domain will also affect its efficiency. For instance, this simulation can determine whether it is better to print content in one location and transport to multiple locations, or print in multiple locations and transport to multiple remote sites. The simulation can determine where it is most advantageous for this digital-physical transformation to take place. While transport and storage may be easier in the digital domain, security and binding may be better in the physical space. Furthermore, when the printed content stream may control the physical manufacturing equipment (e.g. when a barcode on a book block configures a cutting machine), we must have a tool that models such complex interaction.

HP provides workflow software solutions to address digital print productivity issues: Smart Planner and SmartStream Production. SmartPlanner is a job estimation and business planning software. It provides job costs for both digital and conventional presses, in terms of time, costs and margins, covering printing, finishing and supply chain parameters, to establish a breakeven point between different production processes. It helps PSPs to understand the financial impact of getting into a new print market, and the necessary equipments. This year, HP débuted the SmartStream Production Analyzer, a real-time press monitoring software, to help PSP's reach more effective, more efficient production from Indigo presses. This Production Analyzer monitors, tracks and benchmarks the performance of Indigo presses, and aggregate press efficiencies and inefficiencies in terms of press types, shift, and press groups. It provides historical reports of production characteristics (e.g. production performance, up time, printing errors), and informs optimal production planning by providing patterns of exceptions (that is, inconsistencies and unexpected production behavior learned from previous productions).

These solutions are a great first step. In particular, SmartPlanner provides quantitative analysis in units of dollars, which is the ultimate judgment of business success; and Production Analyzer is capable of tracking and tracing dynamic changes of press production. However, today neither provides the complete aid to decision making in end-to-end print manufacturing operations. The technique of multi-level simulation seeks to fortify that analysis with finer resolution and a greater understanding of the internal dynamics of the PSP.

Application Context

Before we explain the role of multi-level simulation, we must further define our terminology and the fields of research that we will be leveraging in our application. This novel application of multi-level simulation will also connect the challenge of operational efficiency of PSPs to an emerging research field called cyber-physical systems.

We define the term a *digital PSP* from a broad range of PSP; a digital PSP close integrates IT infrastructure, digital presses and physical processing devices such as binders and cutter. PSPs are given a set of orders and must process these orders within certain time and cost constraints. In particular, a digital PSP clearly has an IT infrastructure in place to primarily source job orders from the Internet, but also has significant capital investment in physical infrastructure (presses, finishers, binders, etc.). A digital PSP has the twin competitive pressure of being flexible to varied short run job type, and having their equipment run at maximum efficiency.

We identify the tools that we will be using will be coming from the Electronic Design Automation (EDA) industry. The EDA design tools were used to compute electrical waveforms and design single chip layouts, but, as the number of transistors in a device has grown by Moore's law, has evolved to include higher levels of integration from PCB boards, network computer systems and even remote sensing networks. Thus, the EDA software is not a single software tool, but rather set of tools structured in multiple layers of interactions and at different levels of complexity from low-level single level circuits to high-level digital systems. As digital systems have become more complex, the EDA tools coordinate the multiple teams of designers, working in parallel, while ensuring overall end-to-end digital functionality still meet specifications. For example, the design of a next generation cellphone would not be possible without the use of EDA tools and overall tool architecture that took into account multiple-levels of complexity.

The application of EDA tools to the domain of digital PSPs is logical, but not straightforward: while the underlying technologies may be the same, the challenges is not to manage the size of the problem, but rather the heterogeneity of the system -- that a digital PSP simultaneously produces content in a combined IT and manufacturing infrastructure. The challenges in managing a digital PSP come from analyzing and tracking the content even when the content is transformed from digital bits into physical manifestations. The corresponding design information must move with the content even with these changes in medium. While we can virtually assure data integrity in the digital domain, the physical domain becomes a bit of a robust sensing problem. Job in the digital domain, transport is electrical; in the physical domain, it requires a conveyor belt or trained human beings. What distinguishes the PSP from EDA problem is its heterogeneity, and the complexity of the medium (vs. electricity) especially within a physical medium. While not a perfect match, the problem that EDA tools tackle the optimal efficient physical design of digital systems is as close as we are going to get to the design of PSPs.

Multi-level simulation is a tool that clearly has its use both in the digital PSP and the digital system design space. We define multi-level simulation as the integration of multiple level of representation into a single integrated environment, where objects within the simulation often have multiple representations that support same functionality on different levels of modeling. For example, in the digital design domain, the EDA tools support at least 4 major levels of modeling that have varying degrees of precision and representation of the device in question: electrical, switch-level, register transfer level (RTL), behavioral, and system level. These levels of representation allow for an efficient exploration of the design space. In later sections of the paper, we will define our own levels of simulation and show how they can be used to solve many analysis problems within a digital PSP.

The use of the EDA tools for digital PSPs is becoming an emerging field of research called cyber-physical systems. The specific application in growing profitable industry like digital print is of great interest to many EDA researchers.

Our EDA Tool of Choice: Ptolemy

We chose an open-source EDA toolkit, Ptolemy, as our simulation tool for print production systems. Ptolemy is a Java-based, actor-oriented modeling framework for concurrent, real-time, embedded systems. Compared to object-oriented design practice, actor-oriented design emphasizes on the concurrency and

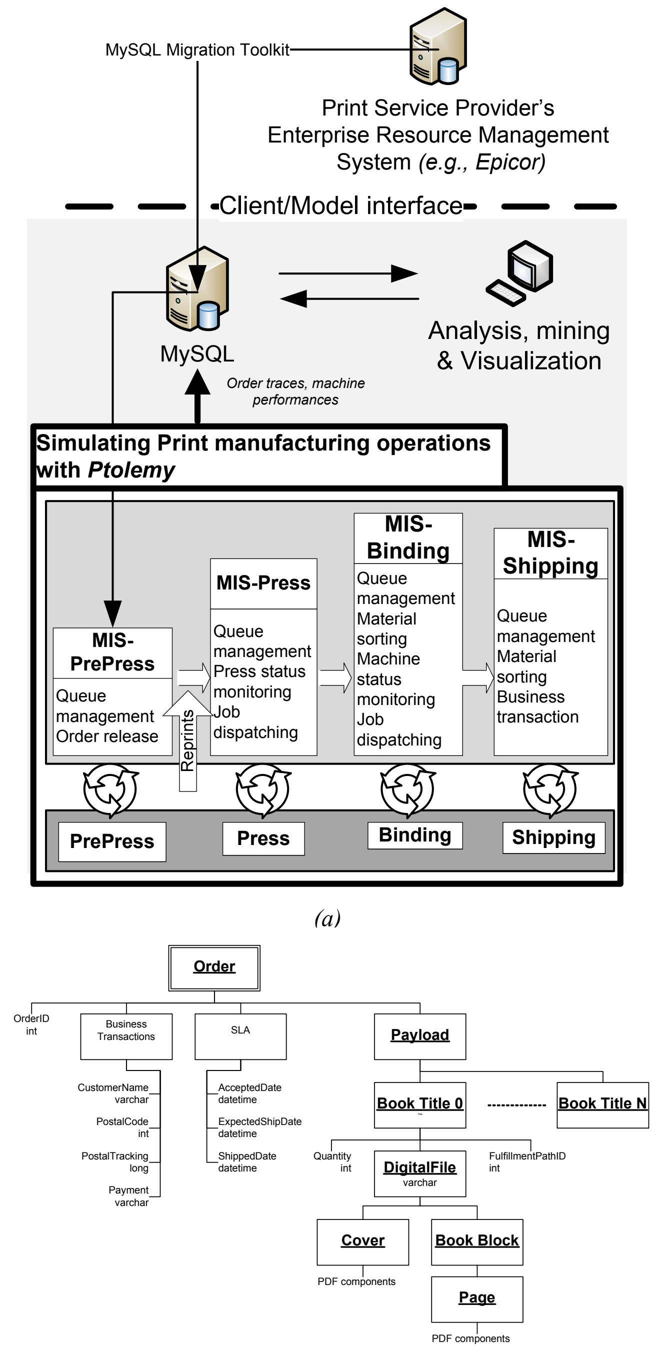

Figure 1. Simulation infrastructure for digital print service providers. (a) The simulator architecture built on the EDA code Ptolemy II. (b) An example instance of multi-level resolution within a simulation. An incoming order is composed of multiple book titles; each digital file is composed of cover and book block, which in turn is composed of PDF components. Depending on desired granularity, the simulator can act at book level, or part level (that is, cover and book block), or pdf component level.

communication among components. Ptolemy implements a set of well-defined models of computation (for instance, continuous time, discrete event, finite state machine) that govern the component interactions. It provides a hierarchical component assembly design environment that enables the use of heterogeneous mixtures of models of computation (e.g., hybrid and mixed-signal models). The print production system and control involves compute, logical and physical components, for which, Ptolemy's ability of blending in different models of computation provides the necessary simulation infrastructure support.

The dominant model of computation that we use to simulate the digital print manufacturing environment is the discrete event model of computation ("Director" in Ptolemy language). In this model of computation, the payload (or content of work) is modeled as tokens. Depending on different granularity during the simulation, a token can be an order, or a book, or a part, or a PDF component. The "actors" in print factory are partitioned into three types: *sources* that produce tokens, for instance, the store fronts that acquire orders, *transformers* that process tokens, for instance, buffers, machines, workers, and *sinks* that consume tokens, for instance, the final shipping process.

The practice of multi-level simulation necessarily integrates both the components themselves and models of other components that are otherwise too difficult or too expensive to be included. For instance, when the desired granularity resides at the PDF component level, it is necessary and most cost effective to integrate a real raster imaging process engine as a component of the simulation model. Ptolemy provides excellent infrastructure to support this hardware-in-the-loop and/or software-in-the-loop paradigm; Ptolemy provides an option to synchronize the simulation time (model time) and the real time (wall clock time) that ensures the seamless integration of models and devices within the same system simulation platform.

Ptolemy provides a simulation infrastructure of the end-to-end print manufacturing operations where data (both operational and financial) can be collected at any stage of the print operations. These dataset can be applied to aid the decision making at both operational and strategic level. It can quantify measurements in the unit of dollar and time that can be directly translate into predicted business performance – adopting the characteristics of HP Smart Planner; it is a dynamic simulation in nature, best cope with highly variable and volatile production environment – adopting the characteristics of HP SmartStream Production Analyzer. However, Ptolemy based simulation by itself does not *automatically* translate into business insights or implementable operations proposals. To enable effective management of the simulation results, MySQL has been integrated within the simulation environment that directly interfaces with other tools for visualization and data mining. The simulation platform shown in Fig. 1 built on Ptolemy backbone completes the cycle of knowledge discovery.

Configuration of Ptolemy

Now let us define the input, internal models parameters, output, and level of modeling of this multi-level simulation to target the Ptolemy tool toward digital PSP domain.

Input to the multi-level simulation is a set of jobs and their intents to be fulfilled from the PSP customers, described in JDF-like format. Each job contains the requirements for media and materials, the processing operations needed to complete the job, the dependencies between processing steps, payment prices and the due dates also come in here.

The internal parameters of multi-level simulation are the current state of the PSP that is controllable by the PSP, e.g. inventory of processing elements, consumables and materials, physical locations of processing elements, separation of inventory over multiple locations, number of employees, shift designations, job scheduling, etc. The number of these parameters is determined by how complex the simulation modeling is.

End-to-end analysis functions are 1) total profit, 2) end-to-end total cost per page, 2) lean manufacturing metrics, work in progress, etc. and 4) evaluation parameters by a third party: profit and loss, or any other measurable outputs such as customer satisfaction. Given for a given input, the multi-level simulation should match closely the measured historical output metrics.

As shown in Table 1, our three primary levels of simulation are defined from the highest to the lowest: job level, Print Description Language (PDL) level, and image level.

Table 1. Levels of Simulation for Digital PSP

Level	Token	Actor
Job	Task Graph	Scheduling and Capacity Planning
Structure	Task Graph + PDL of Content	Content Manipulation, Control via Content
Image	Task Graph + Flattened Image	Integration of Visual Inspection

Job Level: Job tokens are defined as task graphs that monitor the progress of their processing and the amount of materials that are being transported. Job tokens can also be completely divorced from any idea of its inherent content. Only content that affects the processing control need to be abstracted in this type of Token. Job actors must update their processing progress and material levels, if necessary. Job level simulation reflects the high-level capacity planning and bottlenecks, effects of job policy, and job scheduling and routing.

Structure level: The PDL token is a superset of job token with an additional representation of its content as an object in a PDL. PDL token must update their processing progress and material levels, if necessary, and do the necessary transformations on the PDL to reflect the physical processing of the content, e.g. page imposition. PDL token can use the PDL representation for control processing, e.g. looking for and reading in symbolic barcodes. In addition to job level simulation, PDL level simulation reflects PDL manipulations and correctness of content workflow testing (such as variable data printing, mail merge). If physical devices can model their physical actions in PDL equivalent transformation, PDL-level simulation can test and design new software workflows for virtual representations of processing elements, e.g. finishing or cutting equipment.

Image Level: The Image token is a superset of a job token with an additional representation of its content as a set of images. Each image in the set should represent a physically distinct object.

Image actors must update an image token with their processing progress and material levels, if necessary, and do the necessary transformations on the Image to reflect the physical processing of the content, e.g. page imposition. Image actors can simulate sensing data from image/video capture, and use this sensing data for control processing, e.g. visual inspection.

Token Transform	To Job	To Structure	To Image
From Job	N/A	Aggregated Processing of Original PDL	Visual Inspection/ Capture
From Structure	Quality Assurance	N/A	Raster Image Processing (RIP)
From Image	Quality Assurance	Currently Not Allowed	N/A

Table 2. Transformation between digital PSP Tokens

In PSP multi-level simulation, actors have multiple levels of representation, but actors must co-exist and interact. Table 2 shows the allowable transformation matrix of tokens. Unlike digital design, where all levels of representations can be transformed, the PSP design space only allows specific the transformation of its tokens. Structure and Image Tokens can be transformed back into abstract jobs tokens as long as they pass some QA test. Structure tokens use a RIP to transform itself into image tokens, but an image token cannot be transformed into PDL token without ambiguity. A job token may be transformed into a PDL token or image token, by linking the job. This places some limits on our applications of multi-level simulation, i.e. a PDL actor cannot be placed down stream of an Image actor, but the conversion from PDL to image token reflects the irreversible nature of digital to physical transformation.

Demonstration

We will describe four use cases that this multi-level simulation will demonstrate at the conference, showcasing the deep analysis of multi-level simulation.

1. Dynamic Scheduling w/ Content-based policy scheduling: for instance, where scheduling is determined by PDL content such as RIP processing time or ink usage
2. Print Quality Feedback Control: for instance, where downstream visual inspection of printed material can trigger exception, rerouting or reprint of job
3. Stability Analysis of Workflow: for instance, where minor degradation or loss of processing devices or software errors can result in significant capacity problems or failures in quality control
4. Integrated Content and Control: for instance, barcodes placed within PDL workflows control downstream finishers

Conclusion

The advantages of digital print are compelling, but hard to design into workflows due to their complex use of IT infrastructure integrated with physical manufacturing infrastructure. We submit that EDA tools are critical for both the industrial applications and advanced research to meet this challenge.

The EDA toolset is a mature codebase whose primary goals are aligned with the goal of a PSP, the design of physical systems to optimally implement complex functional goals under end-to-end global physical constraints (cost, area, and power). Its computational engines to calculate constrained optimization can be reused to optimize digital PSP.

However, all the EDA toolset is incomplete for all the issues of the digital PSP. Effects that EDA tools must adapt to include the adaptive monitoring and partnership with PSP vendors, the human dimensions, process changes, reliability, the possibilities of incorporating new types of media, and the possibilities of producing new types of products. These all point towards one direction: the simulation infrastructure development including both model creation and computation expansion will be *a continuous improvement* (just like lean manufacturing itself) to ensure the models reflect the change and the computation is stable and robust to the change.

The future path for the EDA tools in digital PSPs is clear: simulation leads to model validation, model validation leads to analysis of incremental design changes, the comparative analysis of exploratory incremental design changes leads to optimization, the automatic iterative search for optimal design paths leads to synthesis. Multi-level simulation is the first link upon the complete tool chain for PSP design.

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Author Biography

I-Jong Lin is the research manager for GPU-RIP Print Services group with Hewlett-Packard Laboratories. He received Ph.D. and M.S. in Electrical Engineering from Princeton University and Stanford University, respectively, and B.S. in Computer Systems Engineering from Stanford University. His research experiences span from VLSI-CAD, digital design, neural networks, video object extraction, to digital print. He is the author of "Video Object Extraction and Representation: Theory and Applications" by Kluwer Academic Publishers. I-Jong holds 13 patents.

Jun Zeng is a senior scientist with Hewlett-Packard Laboratories and has received both Ph.D. and M.S. from Johns Hopkins University. Jun's publication includes 40 peer-reviewed papers and a co-edited book on computer aided design of integrated systems. He was a guest editor of IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems. He serves as termed faculty and member of Ph.D. dissertation committee with Duke University's Electrical and Computer Engineering Department.