LEAN PRODUCT-PROCESS DEVELOPMENT PROCESS TO SUPPORT CONTRACTOR INVOLVEMENT DURING DESIGN

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ABSTRACT

An integrated product-process development model is presented that applies to high-tech AEC facilities. These facilities are extremely complex and involve people from different specialties working together in a design-build team. To be effective, participants need to timely relay their design and production choices so others can provide feedback and proceed accordingly. Guided by the principles of lean manufacturing, we propose the integration of the early design stages with construction. To make this integration work, we advocate the involvement of specialty contractors in the early design. This work proposes a product-process development simulation tool to leverage the involvement of specialty contractors in the early design process. Our system integrates product and process models so that the development of the facility from design through construction can be represented as choices are being made. Initial design choices are conceptual (1-dimensional) whereas later choices lock in the topology and geometry (3-dimensional). We will implement the model on a discrete event simulation engine to specifically focus our attention on uncertainties in the system and delays at hand-offs between project participants. Our goals are to reduce those delays and strategically introduce buffers to help expedite the process overall while at the same time increasing product quality, goals which are part of the theory of lean construction.

INTRODUCTION

The building development process of architectural, engineering, and construction (AEC) facilities is extremely complex. The AEC process most typically starts with an owner defining—in more or less detail—the concept of the facility to be built. This initial concept will evolve in concept development, it will then be detailed and finally built. To be effective in the building development effort, design and building specialists must continuously exchange information and collaborate.

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The windows of opportunity within which to design and build AEC facilities tend to be extremely tight. Engineering, procurement, and construction phases most often overlap in order to shorten the overall time projects take from design through execution. This time pressure causes uncertainty in the development process because work in one phase must progress based on incomplete information from precedent or concurrent phases. In addition, owners seldom have a clear definition of the project requirements at the start of concept development. Changes in project requirements will therefore be expected in the development process and factor in for additional uncertainty.

The design effort of AEC facilities is in practice an iterative process. Most decisions and production choices designers make are primarily a function of the information they have at hand when they think they have to decide and choose. Observation of current practices reveals however that the design process is seldom explicit enough so as to ease the exchange of information, and avoid needless design iteration. In addition, specialty contractors—those who will occasionally detail the design, procure most materials, and build the facility—seldom are involved in the concept development effort.

In contrast, the integration of the concept development process with the fabrication of components and their assembly into a complete product is a principle applied in lean manufacturing systems (Womack et al. 1990, Ward et al. 1995). Similarly, literature in new product development shows some practitioners overlap the concept development and the implementation stages, while postponing the dates when the concept is frozen. These practitioners aim to gain speed as well as flexibility in the process, when market conditions fluctuate and technology evolves rapidly (Iansiti 1995). The involvement of suppliers in the early design development is key to such integration.

The objectives lean theory aims to achieve with the involvement of suppliers in product development are varied. Specifically, such involvement aims to: (1) avoid conflicts between suppliers and manufacturers in the assembly stage that stem from lack of understanding, (2) create conditions for more frequent innovation in product design, (3) reduce meaningless changes in product development and manufacturing processes, (4) create conditions to start manufacturing without complete product information, (5) increase trust and mutual commitment among members involved in the development process, and (6) make upstream downstream-friendly solutions (Womack et al. 1990, Clark and Fujimoto 1991).

The involvement of specialty contractors in concept development is a principle of lean construction theory. How to make this involvement work best in practice is a current research question. The work that follows presents a product-process tool to ease the integration of specialty contractors in concept development and leverage their presence.

RELATED WORK IN PRODUCT-PROCESS MODELING

AEC product-process models integrate information regarding the building design with that regarding the way the design gets built in order to achieve a more meaningful representation of reality. CIPROS (Odeh 1992), one of the first of its kind in construction, is a computer system that links product and process modeling with discrete event simulation. CIPROS enables construction managers to choose alternative construction methods and experiment with their process execution based on product information. CIPROS assumes designers have already committed to a design.

Other product-process models such as CONSTRUCTION PLANEX (Hendrickson et al. 1987) and OARPLAN (Winstanley and Hoshi 1993) better fit in the category of object-activity-resource models. These models map the different components, or objects, of the building product to a sequential network of construction activities. Object-activity-resource models aim to elucidate designers on the impact of different design alternatives to the construction process, but they have not been clear on how to capture construction knowledge of specialty contractors and make it available in the early design stage.

More recent product-process models have taken advantage of postponed commitment strategies to support the building development process. Postponed commitment strategies guide designers to keep track of sets of alternative solutions during the search for the ultimate design solution. In contrast, early commitment strategies provide incentives so each individual can make decisions and choices earlier in the process. Early commitment is usually the method of choice for human designers limited by cognitive ability whereas postponed commitment strategies are easier to implement when computers are being used (Tommelein et al. 1991). Lottaz et al. (1999), for instance, present SpaceSolver, an Internet environment that facilitates project participants to refine the space of design solutions without committing too early.

EXAMPLE PROBLEM: CONFIGURATION OF A LATERAL IN A SEMICONDUCTOR FACILITY

A lateral is a set of routings such as pipes, electrical cables, and ductwork that branch off the main routings between the columns in the subfab of a semiconductor facility. From the valves and openings left on the laterals, other pipes and ducts will branch off to hook up the process tools above in the cleanroom and support tools on the floor of the subfab.

Concept development of a lateral is a configuration problem. Architecture and structural specialties first set the physical limits of the cross-section of the subfab where the lateral will fit in. Other specialties such as mechanical, electrical, and chemical will then allocate parts of the space of the lateral to run the routings of their systems. Examples of design decisions specialties make in the design process are fix the diameter and running height of the exhaust ductwork, and decide whether or not to allocate space for an utility not needed in the immediate future.

The concept development process of the laterals lasts on average six to eight weeks. Rules of thumb, space heuristics, and experiences from previous projects provide the guidelines to help designers solve the configuration problem. The team will mostly work around 2-D drawings such as cross-sections or, though less frequently, around 3-D models of the subfab. In current practice and to our knowledge, no other formal tools of any kind support the coordination process of different design specialties.

Specialty contractors are seldom involved in the decisions being made. Yet, the decisions on the lateral concept will have a major impact on the construction process. The design of the cross-section directly influences the way contractors will plan and build the lateral and then hook up the tools. Design decisions also determine the materials and specialty items contractors will procure, and the labor they will allocate to perform the work. Because some materials may be long lead items, design decisions will affect the readiness of contractors to start construction once the go-ahead has been given.

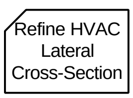
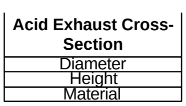
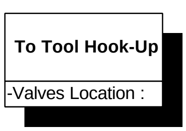
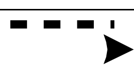
PROCESS DEVELOPMENT REPRESENTATION

The process development model aims to represent the design decisions and production choices the design team makes in concept development. The design team comprises all people who have the capability to influence the decisions and production choices in concept development. The concept development phase encompasses the design effort from the moment owner and designers agree on a concept up to its design detailing.

The process development representation uses the set of symbols summarized in Table 1. These symbols express concept development from a production perspective, i.e., as a set of sequences of design tasks performed concurrently by different design specialties, formal coordination meetings, and informal exchanges of information. Design tasks express the decisions and choices people—such as lead designers and designers—make in the decision-making process. The inputs for each design task are the information on design parameters that result from precedent hand-offs and tasks. The outcome of each design task is the information on design parameters that results from its execution.

At present, we are not modeling the means and methods, neither the people that perform the work at hand. Accordingly, our model is complementary in its approach to other models of human organizations (Jin and Levitt 1996, Lin and Hui 1997).

Table 1. Process Representation Symbols

SYMBOL	NAME	EXPLANATION
	Design Task	Expresses the man-hours designers allocate to make a set of design decisions and production choices. Design tasks may occur in one of two conditions—when input information is available and when it is not. If designers have the information at hand, they execute the task. But if designers do not have the information and are not able to get it, they typically make assumptions to proceed with their work and later revisit the decisions to check the validity of the assumptions.
	Decisions Queue	Denotes the design decisions and production choices that result from each design task. Examples of design decisions are the determination of design loads, capacities and location of equipment, and sizes and materials of system routings.
	Information Hand-off	Expresses the information designers informally exchange between meetings. Such information consists of subsets of design decisions. Before designers start executing their tasks, they typically pull information from other specialties. Once the design task is complete, designers may pull part of the information they produce to other specialties if they think those specialties will need it.
	Weekly Coordination Meeting	Coordination meetings are the main formal way in which designers exchange information in early design. These meetings typically take place once a week and may involve up to 30 people. The meetings involve representatives from different design specialties, owner, and occasionally contractors. In the meetings, people review design decisions, approve some of them, and decide to iterate others.
	Distribution Point	Expresses the effort—in terms of man-hours and tries—each design specialty puts to informally exchange information with other specialties. Informal exchange of information takes place mostly through phone, fax, email, and unscheduled one-to-one meetings around a computer or a pin-up wall.
	Information Push	Indicates the push flow of decisions resulting from a design task to the next task that same design specialty needs to perform.

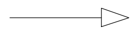
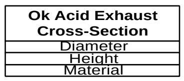
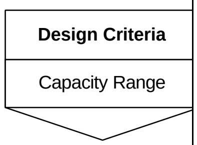
	Hand-off Push/Pull	Indicates the flow of information hand-offs. Such flow can express either hand-offs being pulled from design units or being pushed forward towards other units. In practice, the push or pull nature of the hand-off is typically an individual choice.
	Commitments Queue	Denotes decisions and choices that were confirmed in coordination meetings. Designers typically consider these decisions and choices frozen from this point on and will use them as inputs for subsequent work. Some of these decisions may be passed to procurement and construction if they overlap with concept development.
	Design Criteria	Expresses the design criteria that rule the decisions in each design task. Design criteria result from the translation of project requirements with the help, for instance, of in-house design databases and rules of thumb. Examples of project requirements are the area of the cleanroom, and the rate of production of wafers per week. Resulting design criteria are, for instance, the capacity range of the acid exhaust system.

Figure 1 depicts an excerpt of the process model for concept development. Information Hand-offs that consist of a subset of decisions flow from Distribution Points into Design Tasks. Decisions result from these tasks and fill a Decisions Queue. Design units push decisions from the Decisions Queue to Weekly Coordination Meetings so they can make commitments, which fill a Commitments Queue. The model does not explicitly express exchanges of information and iterations that occur between concurrent tasks performed by the same specialty because it focus on hand-offs between specialties. The model accounts however in the stochastic duration of tasks for the time internal iterations take.

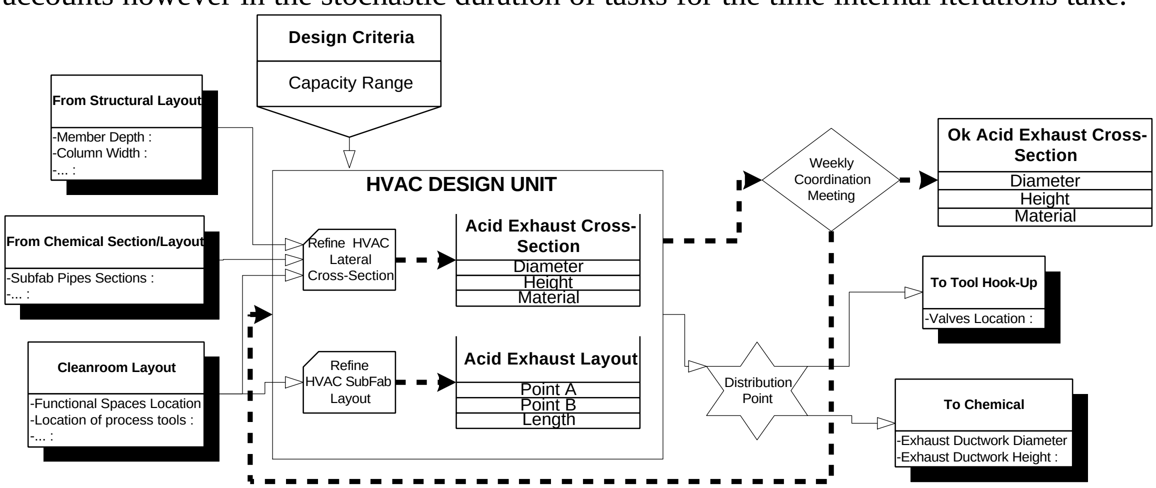


Figure 1 - Excerpt of the process development model for concept development

The product-process model aims to synthesize the perspectives different lead designers have of the early design process. We developed and refined the model through interviews that were focused on the design process of semiconductor facilities. The validity of the model with respect to expressing the process of other kinds of facilities has thus not been tested. Yet, because the model focuses on decisions people make and less on tasks they execute daily, we expect the model to be adaptable.

PRODUCT MODEL REPRESENTATION

The product model represents the decisions the design-build team has to make during concept development. Decisions are expressed at a level of abstraction relevant to the work specialty contractors do and the production choices they make. Such level of abstraction expresses the design decisions for functional areas in a facility. Functional areas are zones that have a programmed function. Each functional area consists of a set of building systems. Each building system is defined by a set of design parameters.

Figure 2 represents an excerpt of the class diagram of the building concept and its initialization for the semiconductor subfab. The model is depicted using the Unified Modeling Language (UML). UML is a graphical notation to model static and dynamic characteristics in an object-oriented environment (Booch et al. 1999). A class diagram presents a static view of a system that describes the properties of classes (sets of objects that have a common structure and behavior expressed in their attributes and operations) and their relationships (Booch et al. 1999).

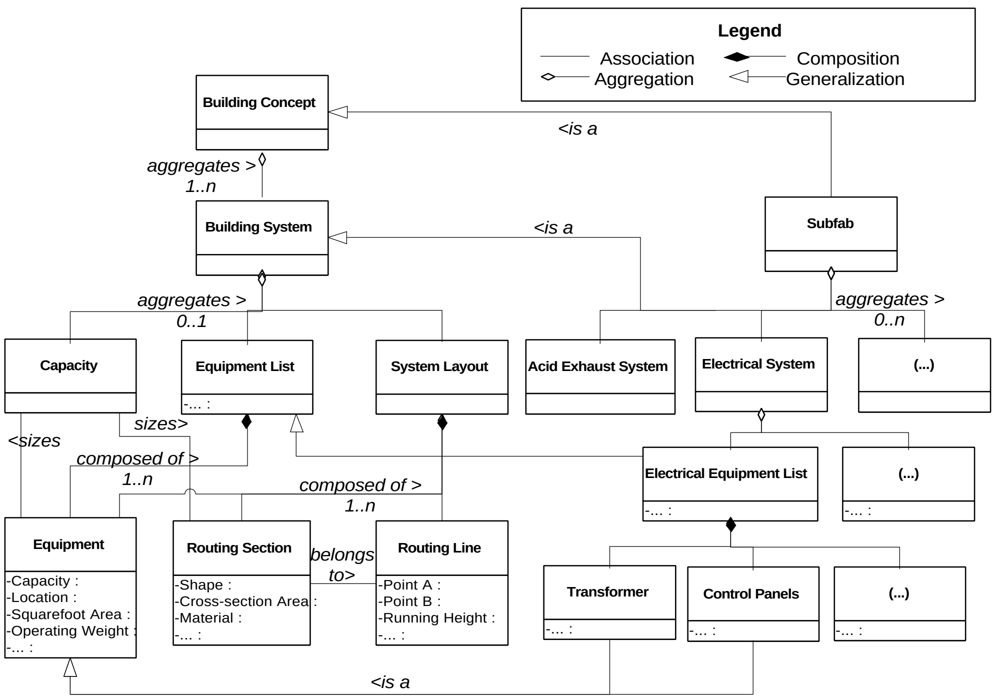


Figure 2 - Excerpt of the Class Diagram for the Building Concept Product Model

Specifics of the product model will gradually evolve in concept development. The space of design solutions will initially remain abstract (0-dimensional) and sets represent alternative solutions. The Building Concept Class is an aggregation of building systems (Electrical System, Exhaust System, HVAC System, etc.), each of which being a part-of the Building Concept class. Subfab in turn is an instantiation of the Building Concept class. Going down one level, the Electrical Building System is an aggregation of three classes: Capacity, Equipment List, and Layout. In turn, Equipment List is composed of pieces of equipment such as Transformer and Distribution Panels, just to mention a few classes. The class Transformer will have some attributes of its own in addition to some that it inherits from the more generic class Equipment.

The refinement of the product model in concept development will be expressed by filling out the attributes of the objects. These attributes correspond to design parameters that characterize the objects such as capacity, voltage, lead-time, supplier, operating weight, geometry, etc. Specifically, the geometry of each object will evolve from an initial abstract representation to a volumetric representation, i.e. from an initial non-dimensional representation to specification of the design parameters for 1-, 2-, and 3-dimensions. In addition, a topological representation will need to tie in the objects so as to express their physical connectivity in the system. The product model proposes to define the topology of the system with the help of classes representing Routing Sections and Routing Lines.

DBE: PRODUCT-PROCESS DEVELOPMENT SIMULATION

DBE (acronym for Design-Build Expediter) will deliver proof-of-concept of a tool to help design-build teams expedite the building development process. DBE implements the product-process model on a discrete event simulation engine. DBE aims to take advantage of simulation to try and compare different strategies teams can adopt in concept development. Simulation will help to recreate the conditions of uncertainty in which projects typically evolve. The results of simulation will enable teams to evaluate the impact of different strategies in the process effectiveness and product quality.

SCENARIOS TO SIMULATE WITH DBE AND EXPECTED RESULTS

We propose to simulate three hypothetical scenarios for the building development process in order to show the impacts of these scenarios in the process and product definition. The first scenario will simulate most common current practices. The second and third scenarios will explore the value of involving specialty contractors in concept development as well as the use of postponed commitment strategies.

Early commitment and lack of integration between designers and specialty contractors characterizes current practices. Designers and owner typically spend few days (frequently less than one week) experimenting and deciding which design concepts to pursue. Once designers and owner agree on the concept, designers start developing it. During the development process designers typically held weekly coordination meetings and commit on design parameters. Specialty contractors seldom are involved in the decisions because they are typically not yet selected.

The second and third scenarios will test the application of set-based concurrent engineering techniques to concept development. Set-based concurrent engineering proposes to develop design by considering sets of possible alternatives and gradually narrowing the sets of possibilities to converge on a final solution (Sobek II et al. 1999). The goal is to keep design alternatives open for a longer time and gradually narrow the space of design solutions. Such strategy promises to increase the flexibility of the concept development process so it can better accommodate uncertainty.

Involving specialty contractors means involving individuals with construction experience such as field superintendents, and labor managers. These individuals will exchange information with designers before the team commits on decisions. Such exchange will create opportunities for the team to develop a more efficient concept from a construction standpoint. Such gains in construction will in turn enable the design-build team to spend more time trying different alternatives in concept development.

In addition, the involvement of specialty contractors in early design creates conditions so they can procure long lead items earlier. The second scenario will study the impact of set-based design strategies in construction while keeping actual long delivery times of equipment and specialty items. The third one will study the impact of set-based design in hypothetical conditions (though reasonable to expect) that reduce delivery times.

ON GOING WORK

On going work will implement some decisions that pertain to concept development of a lateral in a discrete event simulation engine. Simulation will depart from rules of thumb—such as ones used in practice to size the acid exhaust ductwork based on the cleanroom area—to show the impacts to the design process and product definition of uncertainties with project requirements and delays with hand-offs. In addition, simulation will show how the product definition and the building development process may evolve differently according if specialty contractors are involved or not in early design.

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