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Digital manufacturing terminology in the product and the construction industries

Terminologia usada na fabricação digital, nas indústrias do produto e da construção

Marcelo Eduardo Giacaglia[1]
Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo
mgiacagl@usp.br

Arthur Hunold Lara[1]
Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo
arthurlara@usp.br

Norberto Corrêa da Silva Moura[1]
Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo
betomoura@usp.br

ABSTRACT – This paper initially discusses models in manufacturing, then processes in the product industry and finally processes in the construction industry. Although numerical control in machining was introduced in the 1950s, CAE/CAM in the 1970s, and rapid prototyping in the mid 1980s, their use in the construction industry is quite recent. Our research verified that words like mock-up, prototype and product have well established meanings, both in general terms and particularly in manufacturing. Also that, manufacturing processes cannot be simply classified as additive or subtractive. And that the type of physical model produced isn't determined by the type of manufacturing technology. This text uses English as a basis for putting forward correct terminology and classification structures for processes and models, mainly because texts from its language communities, especially the construction industry, present fewer errors. Translations to other languages are given when necessary.

Key words: AEC, digital fabrication, models in manufacturing, manufacturing processes.

RESUMO – Este trabalho trata inicialmente de modelos na manufatura, seguido de processos na indústria do produto e finalmente de processos na indústria da construção. Ainda que o controle numérico na usinagem tenha sido introduzido nos anos 1950, CAE/CAM nos anos 1970, e a prototipagem rápida em meados dos anos 1980, seu uso na indústria da construção é recente. Em nossa pesquisa, verificou-se que palavras como *mock-up*, protótipo e produto têm significados claramente estabelecidos, especialmente na manufatura. Também, que os processos de manufatura não podem ser simplesmente classificados como aditivos ou subtrativos e que o tipo de modelo físico produzido não é determinado pela tecnologia de manufatura utilizada. Este texto faz uso do inglês para estabelecer a terminologia e as estruturas de classificação corretas acerca de processos e modelos, principalmente porque os textos oriundos das comunidades de língua inglesa, mormente na indústria da construção, apresentam menor número de equívocos. Traduções dos termos para outros idiomas são feitas, onde necessário.

Palavras-chave: AEC, fabricação digital, modelos na manufatura, processos de manufatura.

Introduction

The production of an idea requires extensive testing to verify certain attributes before compromising all resources based solely on decisions made in the early stages of the process. Along the product development process (PDP), several forms of representation are employed, in the form of study models, be them 2D or 3D, physical or not. The role of these models is to anticipate potential problems, reduce the uncertainties to a minimum during the process, and to facilitate communication among designers, clients, manufacturers and contractors, so that correct assessments and decisions are made at the proper time.

The PDP comprises distinct phases; each contemplating a constructive stage required by the design, which is the convergent element in the process. Such convergence is made possible through a common language that pervades all stages, as language consistency in the design process is an important factor for a successful outcome.

[1] Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo. Rua do Lago, 876, 05508-080, São Paulo, SP, Brasil.

Each phase in the PDP uses of an appropriate set of study models, related to a required degree of detail that minimizes overall costs, in which each study model, representing the appropriate design attributes for a given stage, is an element of language consistency.

Usage of non-precise terminology for study models within the development team and corporate wide is an improper form of communication, since different types of study models are related to different phases of the PDP, and these are related to the degree of commitment of resources and expected time-to-market. Relative cost of changes between phases is typically tenfold.

The use of CAD/CAE/CAM (digital manufacturing or fabrication) in the construction industry is quite recent worldwide and incipient in the developing countries. In the academic community, research conclusions and proposals in the field also vary accordingly. Academic research is vital to the introduction and adaptation of these technologies to the specificities of the construction industry, from the object, through the building, up to the urban scale.

Ghery Technology (GT), a key player in the use of digital design and fabrication in the construction industry, was founded in 2002, from ideas and practices borrowed from the aerospace industry ten years earlier. Another well known example of the introduction of product manufacturing technology in the construction industry is the work of Lawrence (Larry) Sass, an associate professor in digital fabrication at MIT. Both are from the English speaking architecture community.

In some developing countries, in spite of the existence of a well established capital goods and product industry, research papers by academics of the construction industry reflect a shallow understanding of the processes and the role of models in manufacturing. In some cases, proposals have become naive, in belief that the construction industry is isolated from the product design and manufacturing industry and, consequently, that terminology is not related. The manufacturing industry has undergone dramatic changes in pursuit of efficiency in the product lifecycle in a competitive globalised market, and consequently the terminology and etymology related to these processes are globally diffused.

In our Faculty, we have two undergraduate courses. One is Architecture and Urbanism (A&U) and was created in 1948. The other, Design, was until recently (and still is) part of the A&U course. The Design course includes industrial product design and visual communication. Although based in the A&U Faculty, other schools in our University have significant participation in this new course: Business and Marketing, Fine Arts and Visual Communication, Production and Materials Engineering and Computer Science.

The Design course shares installations (machinery) and staff, professors and technicians with the A&U and Engineering courses. Not only school staff, professors and technicians, but students, from different courses, engineering, design and architecture, working in the same labs and shops, in a collaborative manner must use the same nomenclature, not only in ours but in other universities, worldwide.

This paper initially discusses the role of models in manufacturing and then process classification in the product industry and finally their implementation in the construction industry.

Models in manufacturing

In manufacturing, it is necessary to distinguish between input, process and output. Modeling is a process while a model is an input or output of that process. Physical modeling or manufacturing produces physical objects from raw or processed materials, object components, energy and currently computer generated electronic information. The information provided by a computer is usually referred to as a digital or virtual model.

The general case for all (physical) product models, a (physical) study model is a representation of some aspect of the design to be tested. For Kalpakjian and Schmid (2006, p. 13) "Product design often involves preparing analytical and physical models of the product as an aid to studying factors such as forces, stresses, deflections, and optimal part shape". The link between earlier study models of a product and the actual product is the prototype.

General definitions for specialized study models, mock-up, scale model and prototype found on English dictionaries, are given as follows.

According to Webster (1966):

> "mock-up, *n* a scale model , usually full-sized replica in wood, cardboard, canvas, etc. of a structure, apparatus or weapon, used for instructional purposes, to test the design, or, in military use, as a dummy to draw enemy fire away from a vulnerable point."
> "prototype, *n* [Fr. from Gr. prototypos; protos, first, and typos, type, form, model.] an original or model after which anything is formed; the first thing or being of which anything is formed; the first thing or being of its kind; a pattern; exemplar; archetype."

According to Collins (2001):

> "mock-up *n* 1. a working full-scale model of a machine, etc. for testing, research, etc."
> "prototype *n* 1. one of the first units manufactured of a product, which is tested so that the design can be changed if necessary before the product is manufactured commercially."
> "scale *n* … 3a. the ratio between the size of something real and that of a representation of it. 3b. (*as modifier*): *a scale model*."

In the product engineering, English language community, for example, De Garmo *et al.* (1999, p. 231-232) state that "Often a prototype or working model is constructed to permit a full evaluation of the product". Kalpakjian and Schimd (2006, p.14) also define prototype as "an original working model of the product".

As for product design and engineering in Brazil, Naveiro and Romeiro Filho (2010) define some virtual and physical models:

- a virtual prototype or an electronic model, is a 3D computer model, used for general visualization, assembly verification and/or functional simulations;
- a mock-up, is a partially functional representation of a product for simulation of use and aesthetics and ergonomics evaluation;
- a scale model is a non-functional representation, usually in reduced scale, for general product evaluation;
- a prototype is a functional model having almost all of the intended product's characteristics, for field and consumer testing, preceding serialized production and release. Some products like buildings or ships are actually prototypes.

The origin and general definition for *protótipo* in Portuguese is the same as of prototype in English. Ferreira (2009) defines it as "First type or example, original; a product fabricated individually or artisanal, following the specifications of a design for serial production, whose purpose is to serve as a test before industrial scale of production, or market release".

Table 1 exhibits correspondent names, in different languages, for the above cited specialized physical models.

Table 2 shows a compilation, from several sources, of the usage of these models, in association with the relative cost (order of magnitude) of changes in design among PDP phases.

Table 2 exhibits the above cited specialized models but not of the general case, which can span from the pre development phase up to detail design. Nowadays, in order to reduce product development times and costs, early study models are being replaced by digital models in computer simulations (Kalpakjian and Schmid, 2006, p. 41; Naveiro, 2010, p. 293).

Table 1. comparative terminology of types of models by language.

English	**Scale model**	**Mock-up | Mockup**	**Prototype**
French	*Maquette*	Mock-up	Prototype
Italian	*Modello in scala | Plastico*	Mock-up	*Prototipo*
Portuguese	*Maqueta | Maquete*	Mock-up	*Protótipo*
Spanish	*Maqueta*	Mock-up	*Prototipo*

Table 2. Model usage and the relative cost of changes in design, and PDP phase.

Phase (1)		**Product specific.** (2)	**Relative cost of changes in design** (3)	**Use of models** (4)			**Product**
				Scale / Volume	Mockup	Prototype	
Pre development							
Development	Informational Design						
	Concept Design	raw	10				
	Embodiment Design	firmer	100				
	Detail Design / Process Planning	firmer	1.000				
Manufacturing	Tooling / Plant Preparation	frozen	10.000				
	Production / Product Launch		100.000				
Post development - use / maintenance			1.000.000				

Notes: (1) Adapted from Ferreira and Naveiro (2010, p. 149) and Groover (1996, p. 979). (2) Adapted from Khan and Raouf (2006, p. 141). (3) Adapted from Volpato *et al*. (2007, p.36). (4) Adapted from Volpato *et al.* (2007, p. 31).

Digital models in manufacturing range from simple 2D drawings to a complete set of instructions for manufacturing a product. Two-dimensional drawings are usually intended for documentation and as a specification for manual (or up to some degree of mechanized) construction of objects. Three-dimensional computer models can be used for simple visualization in CAD, to simulations in CAE, and on to manufacturing in CAM systems.

Usage of the term virtual prototype (*protótipo virtual* in Portuguese) is wrong. Better alternatives for digital model are digital (or virtual) mock-up (e.g., Atmani *et al.,* 2008) or *maquette numérique* (e.g., Koehl, 2003). The latter translates to Portuguese and Spanish, as *maqueta digital*.

Lack of knowledge of the role of models in manufacturing can lead to disaster. Unless, otherwise it can be proven that computer simulations are capable of predicting all aspects of product behavior in the real-world.

Liou (2007, p. 11) states that the Boeing 777 airplane was assembled 100% digitally, without the need for 'physical prototypes', but (in contradiction) he also affirms that "Only a nose mock-up to check critical wiring was built" and that "on June 12, 1994, the first 777 prototype took off on its maiden flight". This was indeed the actual prototype (Figure 1), since the first delivery occurred on May, 1995 (Figure 2).

We can conclude from the above that, in the product development process, the kind of model considered is determined by its purpose, as shown on Table 3.

Manufacturing processes in the product industry

Manufacturing is the process, manual or mechanized, of converting raw materials and/or products (components) into other products. Kalpakjian and Schmid (2006, p. 3) distinguish discreet from continuous products. For Khan and Raouf (2006, p. 6), a product can be discreet or an assembly, composed by a structure or a mechanism. A structure is static while a mechanism has moving parts.

Groover (1996) states that the basic building blocks of manufacturing are materials, processes and systems

Figure 1. Boeing 777 airplane - 1st prototype.
Source: http://www.777fleetpage.com/

Figure 2. Boeing 777 delivered to United Airlines - 1st product "off the line".
Source: http://www.airports-worldwide.com/articles/article0090.php

Table 3. Model taxonomy in product development.

<table>
<tr><td rowspan="8">Product model</td><td colspan="3">Representation of some aspect of the design to be tested, which can also be one of the following:</td></tr>
<tr><td rowspan="2">Analytical model</td><td colspan="2">A drawing or mathematical description, which can also be a:</td></tr>
<tr><td>Digital model</td><td>Computer simulation of a physical model (Figure 3), design data for product or component manufacturing and/or documentation</td></tr>
<tr><td rowspan="4">Physical model</td><td colspan="2">Generic physical study model, which can also be one of the following:</td></tr>
<tr><td>Scale model</td><td>For general evaluation</td></tr>
<tr><td>Mock-up</td><td>Full scale, for aesthetics (Figure 4) and/or ergonomics evaluation (Figure 5), which can include simulation of use</td></tr>
<tr><td>Prototype</td><td>Field and/or consumer testing before serial production or release; full scale and fully functional</td></tr>
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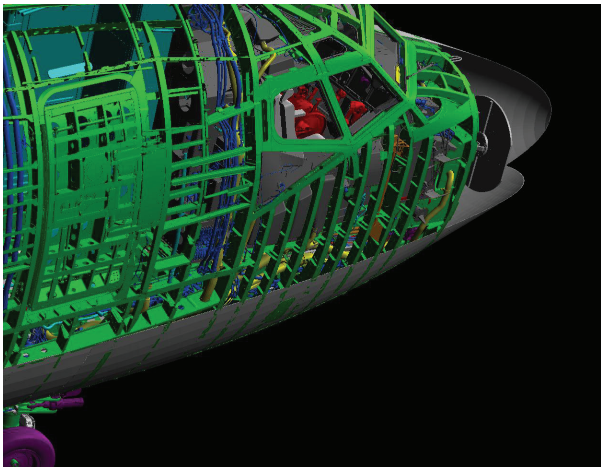

Figure 3. Digital model used in the development of Boeing 777.
Source: http://seattle.siggraph.org/talks/1998.04/

Figure 4. Mock-up of a racing car – for promotional purposes.
Source: http://www.apriliaforum.com/forums/showthread.php?t=188471

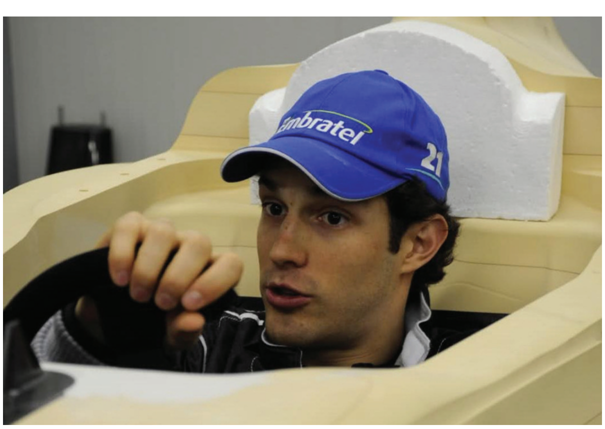

Figure 5. Mock-up of a cockpit – for ergonomics evaluation.
Source: http://forums.autosport.com/lofiversion/index.php/t111348-450.html

(facilities, equipments, procedures and people). Manufacturing processes are classified as follows:

a. processing operation
    i shaping process
        ▪ casting and molding
        ▪ particulate processing
        ▪ deformation process
        ▪ material removal
    ii property enhancing (usually heat treating)
    iii surface processing
b. assembly operation
    i permanent joining
    ii mechanical fastening

Groover (1996, p. 15) observes that more than one processing operation is usually required to transform the starting material into final form, as illustrated in Figure 6.

De Garmo *et al.* (1999) provide a similar classification:

i. casting, foundry and molding
ii. forming and metalworking
iii. machining (material removal)
iv. heat treating
v. surface treatment (finishing)
vi. joining and assembly
vii. other, e.g. packing

De Garmo *et al.* (1999, p.18) affirm that such classification is far from perfect and that manufacturing processes are not exclusive.

Kalpakjian and Schmid (2006) provide a similar classification:

i. casting
ii. forming and shaping
iii. machining and finishing
iv. joinig
v. nanofabrication

As new materials are developed and efficiency is pursued new processes or types of processes are added to the existing. Kalpakjian and Schmid (2006) provide a historical list pertaining to materials development and manufacturing processes, from 4000 B.C., and earlier, to the end of the 20th Century. For them "A technology which considerably speeds the interactive product development process is the concept and practice of rapid prototyping (RP) – also called solid freeform fabrication" (Kalpakjian and Schmid, 2006, p. 581).

Kalpakjian and Schmid (2006, p. 21, 582) classify the existing, most common, RP techniques - stereo lithography, fused deposition modeling, three-dimensional printing, laminated object manufacturing, ballistic particle manufacturing, and selective laser sintering – under polymer processing and/or powder deposition, in forming and

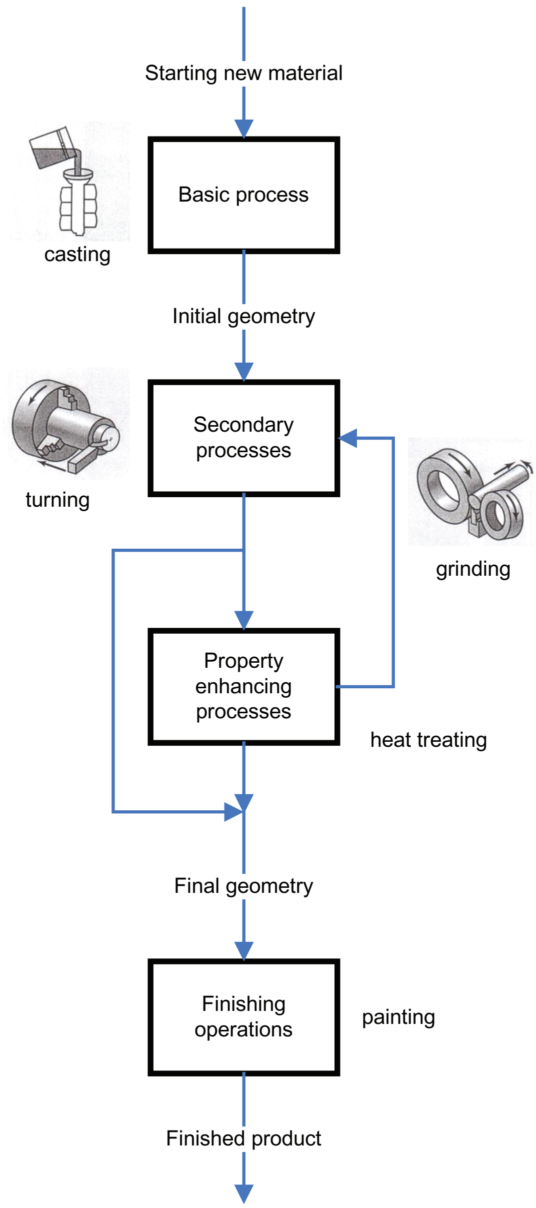

Figure 6. Typical sequence of processes required in part fabrication.
Source: Adapted from Groover (1996, p. 969) with images from Kalpakjian and Schmid (2006).

shaping operations. These authors classify RP processes into three major groups: subtractive, additive and virtual (Kalpakjian and Schmid, 2006, p. 582), although according to the same authors (Kalpakjian and Schmid, 2006, p. 14) RP relies on CAD/CAM systems. Dependence of RP on CAD data was also cited by Groover (1996, p.981).

Kalpakjian and Schmid (2006, p. 14) define virtual prototyping "Virtual prototyping is a totally software form of prototyping, and uses advanced graphics and virtual reality environments to allow designers to examine a part".

Kalpakjian and Schmid (2006, p. 21-22, 581) also observe that although process selection depends on the shape to be produced and properties of the materials, there is usually more than one method of manufacturing a part from a given material and that each process, including RP, has its own production rates and product cost.

Furthermore, they state that, for RP "These techniques are now being advanced further so that they can be used for low-volume economical production of actual parts to go into products" (Kalpakjian and Schmid, 2006, p. 581).

Liou (2008), a feverous adept of the use of the so called RP technologies, uses the terms model and prototype interchangeably. This is a misconception because, although there is general acceptance of modeling and prototyping as synonyms, most authors affirm that prototyping, including RP (e.g. Kalpakjian & Schmid, 2006 p.594), produces models.

Liou (2008, p. 218) states that CNC machining cannot be considered RP because:

(i) requires skilful human intervention to help plan the operations;
(ii) often requires custom fixturing and special tooling;
(iii) machining has inherent geometrical limitations.

In this sense, existing alleged RP processes shouldn't also be considered totally RP, because they don't fulfill completely the above conditions. Silva (2007, p. 135-136) describes typical post-processing, finishing and property enhancement processes for RP, which often requires human intervention, a deficiency according to Volpato (2007, p. 73, 75, 78, 92, 94). Furthermore, Liou (2008, p. 288-289) cites a hybrid additive-subtractive process designed to overcome the use of supporting structures, a kind of geometrical limitation of many RP processes.

A citation that also leads to the conclusion that RP does not necessarily produce prototypes is given by Volpato *et al.* (2007, p. 29):

> [...] parts obtained from RP technologies don't have the same technical characteristics of those obtained through injection. A reason for this is that most RP processes can't use the materials used in final production. Also, the effect of layer deposition is commonly visible in many processes.

It becomes clear from the above that, the kind of physical model considered is not determined by the manufacturing technology or process, and that prototyping in general, or RP in particular, do not necessarily (as usually is the case) produce prototypes, but intermediate models. RP can be capable of producing actual products, hence the terms Rapid/Direct Manufacturing and Rapid Tooling

(Kalpakjian and Schmid, 2006, p. 594) or Direct Digital Manufacturing (Liou, 2008, p. 159). We find that DM or DDM are better terms than RP.

We recall another form of classification (Amber and Amber, 1962 *in* De Garmo *et al.* 1999 p. 24), based on the degree of mechanization or automation, or the human attribute replaced:

A (0) None;
A (1) Energy – 1st industrial revolution machines;
A (2) Dexterity – single cycle, self-feeding, stops automatically;
A (3) Diligence – repeats cycle automatically, open loop (no positional feedback);
A (4) Judgment – measures and compares results with desired position or size, and makes adjustments to minimize errors (closed loop control);
A (5) Evaluation – adaptive control, deductive analysis;
A (6) Learning (by experience, limited self programming) and; A(7) – Reasoning (exhibits intuitions, relates causes to effects) – academic research;
A (8) Creativeness (performs design unaided) and; A(9) – Dominance (commands others) – science fiction.

Current CNC and RP technology reaches level A(4). A hybrid additive, subtractive and assembly, cellular DDM centre, capable of determining optimal strategies (selecting among available inputs and processes) to obtain a given output, would be on level A(5), as illustrated on Figure 7.

Manufacturing processes in the architecture and construction industry

Technical activities in construction can be classified by the type of intervention, according to ABNT (1995). ABNT's classification makes distinction between new and existing buildings.

Categories for new buildings are construction and prefabrication (including precast concrete). Construction is a process that consists of the building or assembling of infrastructure. Building construction is the process of adding structure to real property. Prefabrication is the practice of assembling components of a structure in

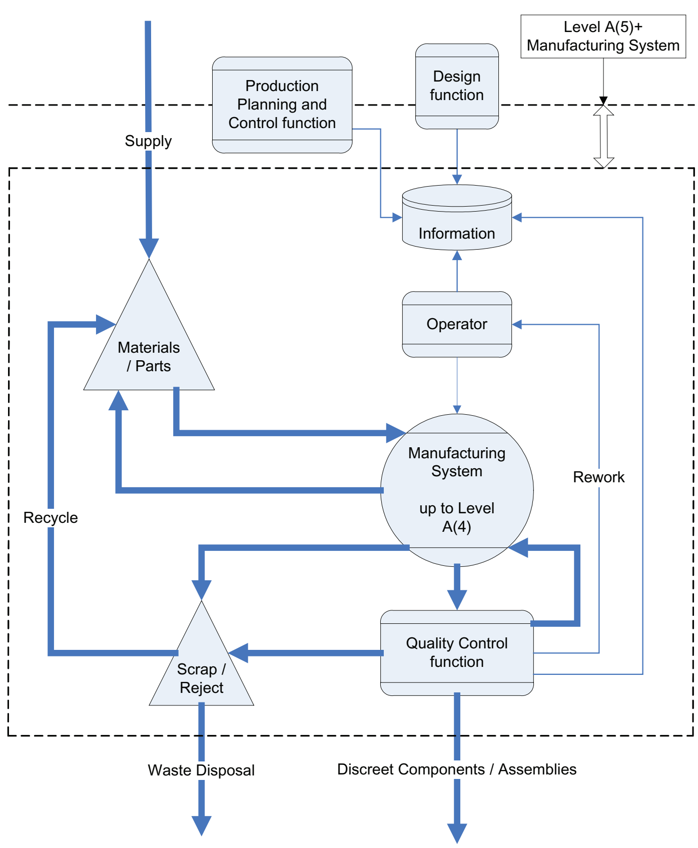

Figure 7. Illustration of an Amber and Amber's A(4) and A(5) degrees of mechanization and automation in manufacturing discreet products/assemblies

a factory or other manufacturing site, and transporting complete assemblies or sub-assemblies to the construction site where the structure is to be located. The term is used to distinguish this process from the more conventional construction practice of transporting the basic materials to the construction site where all assembly is carried out.

Besides assembly (mechanical fastening or permanent joining) of components, construction, both industrialized and conventional, involves processes easily identified as casting, surface or heat treatment.

In the case of existing buildings, there are more categories: extension, reduction (deconstruction or demolition), relocation, repair (also maintenance and reform), restoration (also conservation and preservation), rehabilitation and renovation (and retrofitting). Precise definitions for each category are given, for example, by Petzet (1994).

Building extension refers to construction while deconstruction refers to disassembly. Demolition is an expedient means of clearing a site of its building that will most likely end up as rubble in a landfill, much the same way as a discarded product. The term DfD - designing for deconstruction, is the correspondent of DFMA - designing for manufacturing and assembly.

Relocation is the process of moving a structure from one location to another. There are two main ways for a structure to be moved: disassembling and then reassembling it at the required destination, or transporting it whole.

Maintenance is the limited, continuous preservation work such as cleaning, painting, removal of plant growth (surface treatment), re-nailing of roof tiles (permanent joining). Repair is work that occurs at greater intervals and is often necessitated by inadequate maintenance and involves fixing (surface treatment or assembly) any sort of mechanical or electrical device should it become out of order or broken.

Restoration is the process of the renewal and refurbishment of the fabric of a building. The work performed on a building in order to return it to a previous state of conservation. Building restoration can be thought of as that set of activities which are greater than year-to-year maintenance, but which by retaining the building are less than a demolition and the construction of a new building. Restoration involves cleaning (surface treatment), major repairs and/or rebuilding, the replacement of severely damaged or missing parts of the building (assembly).

Conservation is the action of accurately revealing, recovering or representing the state of a historic building, as it appeared at a particular period in its history, while protecting its heritage value. Work is often performed to reverse decay, or alterations made to the building after its initial construction.

Preservation is the action of protecting, maintaining, and/or stabilizing the existing materials, form, and integrity of a historic place or of an individual component, while protecting its heritage value. Preservation can include both short-term and interim measures to protect or stabilize the place, as well as long-term actions to retard deterioration or prevent damage so that the place can be kept serviceable through routine maintenance and minimal repair, rather than extensive replacement and new construction.

Rehabilitation (or modernization) is the action of making possible a continuing or compatible contemporary use of a historic place or an individual component, through repair, alterations, and/or additions, while protecting its heritage value.

Renovation (or remodeling) is the process of improving a structure. Retrofit refers to the addition of new technology or features to older systems. Both are usually complex, but are describable in terms of processes, for example, repairs, rebuild, finishes.

The majority of the processes related to the above activities are achieved through manual labor. There has been significant industrialization of components and even some automation in construction, but in the overall it is much behind that of product manufacturing. The current lack or low degree of automation in the architecture and construction industry is mostly due to cultural factors.

On the cultural side there have been a growing number of initiatives, like those of Ghery Technologies (Figure 8) and Lawrence Sass cited in the beginning of this text. On the technological side, digital models have improved from hand drawings to Building Information Models (BIM). While BIM systems aren't yet capable of automated construction of buildings, the same holds for CAD/CAE/CAM systems for the production of a non-trivial product. In both cases this is because current manufacturing technology is still bellow Amber & Amber's A(5) level of automation.

It becomes clear that all the above building intervention categories can be related do processes that are or can be the same as the ones listed in the product manufacturing industry section of this paper. This becomes more evident with the industrialization of construction, in pursuit of the same or similar technologies.

In 2004, the Bureau of Labor Statistics of the US Department of Commerce published a report, according to Teicholz (2004), which showed that labor productivity in the construction industry had declined in the previous forty years, not only when compared to other economic segments, but also in absolute terms (Figure 9). It became evident that a change in culture was necessary - the introduction of methods and technologies of the product industry.

These methods and technologies include BIM, digital fabrication, and even IPD – Integrated Project Delivery (AIACC, 2007), a concept similar to Concurrent Engineering (Groover, 1996, p. 979; Kalpakjian and Schmid, 2006, p. 11). Through these initiatives cons-

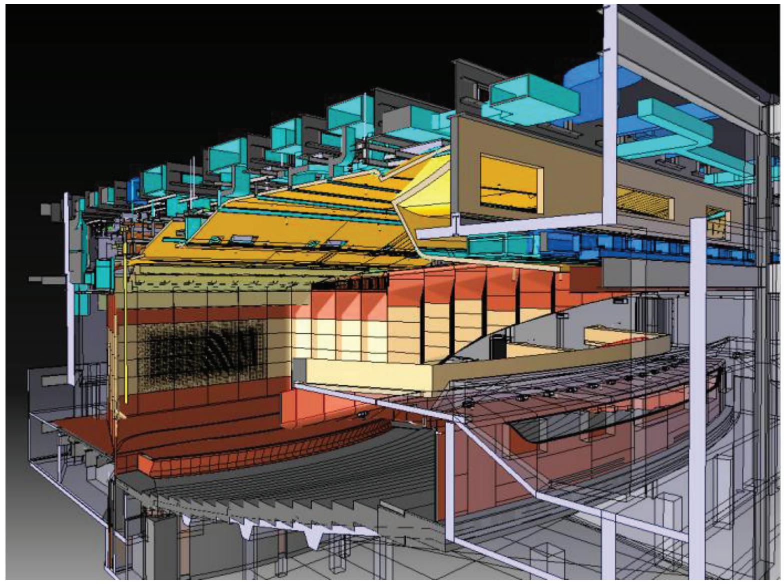

Figure 8. Digital model for the renovation of the Alice Tully Hall (Lincoln Center, New York): interior panels went directly from the 3D model to fabrication.
Source: http://www.gehrytechnologies.com/index.php?option=com_jportfolio&cat=3&project=36&Itemid=25.

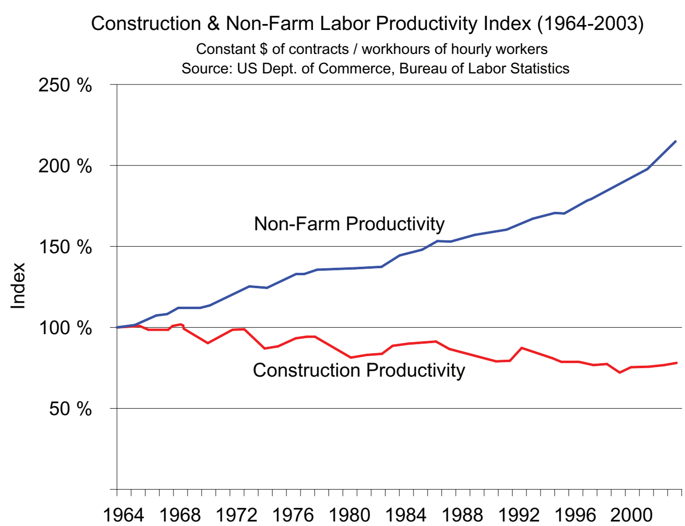

Figure 9. Construction and non-farm labor productivity index in the US.
Source: Adapted from http://www.aecbytes.com/viewpoint/2004/issue_4.html

truction processes become more efficient. The artisanal, improvised, inefficient methods are eliminated, as is the waste of materials. A scenario where architects, civil engineers, product designers and engineers work together with contractors and construction workers, in which all actors have knowledge of processes and usage of digital manufacturing technologies.

Conclusion

We conclude from our research that, in the product development process:

- The kind of model considered is determined by its purpose, not by manufacturing technology or process. Existing RP systems most likely produce mock-ups or scale models. Some RP systems can produce prototypes and even final products, if they are able to perform accordingly;
- Two orthogonal classification structures exist for manufacturing processes; one based on alteration of form and the other on the degree of mechanization or automation. A level A(4) of automation is required for digital manufacturing. The distinction between additive and subtracti-

ve processes is a creation of the RP language community. Because first processes where all "additive" (layered material deposition), there is a tendency to distinguish them from "subtractive" processes (machining). A better and broader term for RP would be DDM, the fabrication of components directly from computer models. In this sense, rather than being a distinct branch, RP is a specialization of digital fabrication technology;

Architects and civil engineers, when shifting towards automation in construction and digital manufacturing, cannot expect to be dealing with the same kind of worker found in artisanal building construction. They will be communicating with very well trained, skilled worker of the type found in modern factory floors, a community accustomed with precise terminology and strict design language throughout development and production.

This paper aimed to search for and put forward the correct terminology and classification structures pertinent to the product design and manufacturing industry, to argument that acceptance of these terms is a necessary requirement for fully benefitting from the introduction of methods and technologies of the product industry into construction, a process that has already started and is irreversible.

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