Empire State Building Project: Archetype of "Mass Construction"

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Abstract: Analysis of historical projects, with the dual benefits of hindsight and modern concepts of construction systems, can help fill the gaps in our theoretical understanding of production in construction, which have increasingly been identified as a barrier to progress in improving construction project management. The richness of the historical record describing construction of the Empire State Building provides a unique opportunity to analyze and compare it with the paradigms of craft, industrialized, and lean construction. Its size and its record rate of construction, which has not been broken since for tall buildings, make it of prime interest. The project progress was reconstructed using line-of-balance software and its different flows were assessed. The results lead to the conclusion that it is an archetypal example of what we propose be called "mass construction." This enables a richer understanding of the taxonomy of production systems in construction, and should aid theoreticians and practitioners alike to devise better production systems for construction projects.

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Introduction

"The Empire State Building is not *any* skyscraper. Extraordinary in 1931 for its height, sheer size and unmatched speed of erection, the tower has since been exceeded only in height and mass" (Willis and Friedman 1998). The Empire State Building (ESB) set speed records for both design and construction and was completed well within its initial budget (Tauranac 1995; Willis and Friedman 1998). The contracts with the architects were signed in September 1929 and the first structural columns were set in April 1930. Only 1 year later, the building was fully enclosed, with a height equivalent to 102 stories, $200{,}000\ \mathrm{m}^2$ of rental space, 57,000 t of structural steel, $48{,}000\ \mathrm{m}^3$ of concrete, 10 million bricks, and the involvement of almost 3,500 workers on-site on peak days (Willis and Friedman 1998).

The rate of construction of apparently similar tall office buildings appears to have declined steadily since that time (Partouche 2009). Fig. 1 shows the construction rates for the world's 100 tallest high-rise buildings built between 1929 and 2008, in terms of: (1) the number of floors per year and (2) the floor area built per year of construction. These are not literal measures—buildings top out well before they are complete—but rather represent gross measures of overall construction rate in proportion to height and size. While the chart does not account for factors such as safety, quality or design complexity, the trend for construction of tall buildings is toward slower rates. This appears to be anomalous when one considers the technological advances that have been made over this period in construction equipment, materials, methods, communications, and computing, all of which presumably make construction more efficient.

Recent developments in the understanding of project and production management in construction provide a new and fertile basis for revisiting record-setting construction projects such as that of the ESB. Warszawski (Warszawski 1990) provided formal definitions for industrialized construction, adopting the prevalent deterministic approach to construction management embodied in the critical-path method. Koskela's report on the applicability of the "new production philosophy" to construction (Koskela 1992), and Ballard's development of the Last Planner System (Ballard 2000b; Ballard and Howell 1998), introduced an alternative way of thinking of production systems in construction.

The primary thrust of this work was to supplement the "transformation" view, in which projects are broken down into hierarchies of activities at numerous levels of resolution and then managed as separate packages, with a "flow" view, in which projects are seen as continuous processes in which value is progressively added to construction products. The flow view enables explicit consideration of cycle times, work in progress (WIP) and time buffers between production activities, and nonvalue adding activities. The three views of transformation, flow, and value, have been collectively termed "TFV" (Koskela 2000). Subsequent papers on the nature of flow in construction (Bertelsen et al. 2007) and the structure of the construction industry (Bertelsen and Sacks 2007) are more recent attempts to define theoretical aspects of what has come to be called "lean construction."

These developments in theoretical thinking are the basis for our analysis of the ESB project. While the transformation view has traditionally been the basis for construction research, we base our analysis on the flow view. The research aimed to reconstruct

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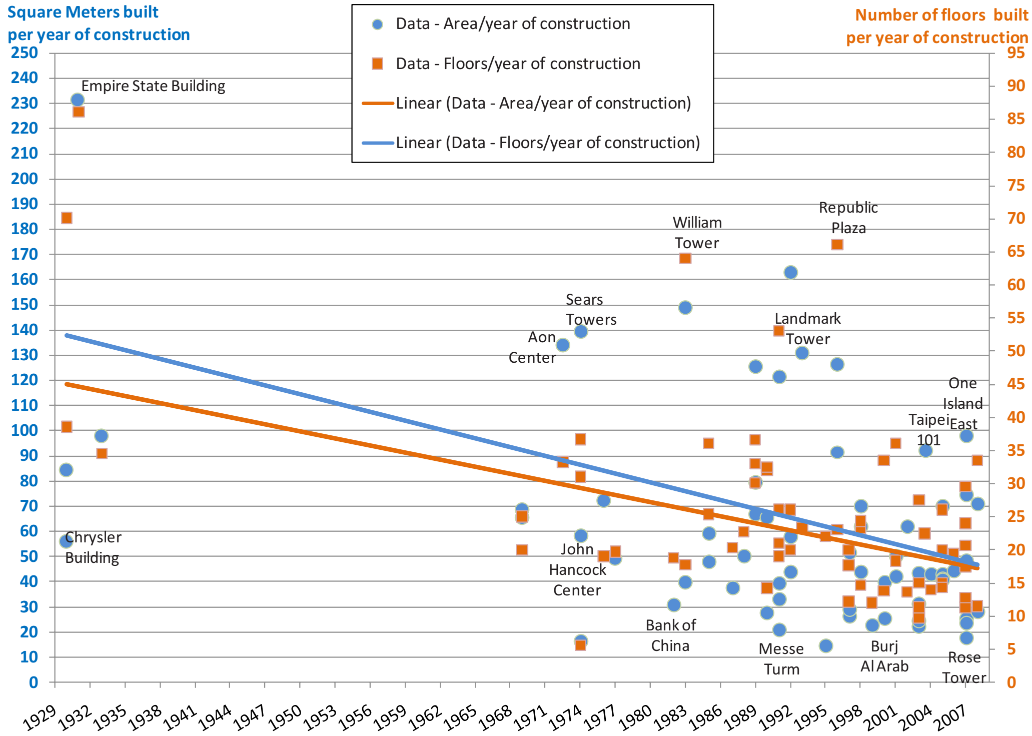

Fig. 1. Construction rates for the world's 100 tallest buildings built between 1929 and 2008 (Partouche 2009). Data sources: Emporis Standard Committee (Emporis 2009) and SkyscraperPage (SkyscraperPage 2008).

the project process, to analyze it using the flow view, to discern the production system paradigms evident in it (such as craft, industrialized, and lean construction), and to use the results to reflect on our understanding of those paradigms. The methodology was to reconstruct the process using line-of-balance flowcharts (Henrich et al. 2005) and to analyze the project subject to four aspects of flow (work flow on-site, flow of products in the supply chain, information flows, and the material handling logistics on-site).

The next section describes the ESB project and the reconstruction of its line-of-balance schedule. This is followed by an analysis of the project subject to the flow view of construction. A review of the progression of production systems in manufacturing and construction follows, as a background to a discussion of the place of the ESB project in that progression.

Reconstruction of the Empire State Building Project Schedule

The first step in analyzing the ESB project was to reconstruct its schedule. The planned and actual start and end dates of the project, and of most of the key activities, are available in the historical record. A detailed notebook, titled "Notes on Construction of the Empire State Building," was compiled during the construction in 1930 by Starrett Brothers and Eken, the general contractors of the project, and published by Carol Willis, founder and director of the Skyscraper Museum in New York City (Willis and Friedman 1998). The book includes a highly detailed record of a "daily job activity" diary log entry, for Thursday, August 14, 1930, which is the day when the greatest number of workers was employed on-site: 3,439 people. Every activity executed on the day is recorded with the name of the subcontractor that executed it, the number of workers who performed it, a complete description of the action executed, and its precise location in the building. The "Virtual Archive 2" (Willis 2005), an interactive interface that provides access to the Skyscraper Museum's unique collection of photographs of the construction of the ESB, was an additional source of dated information.

To begin, the activities for Thursday, August 14, 1930 were compiled in a table with the floor numbers in the row headers and the 26 different subcontractors listed in the column headers with subheadings for the activities they each performed. To simplify the process, some activities that did not influence the planning were ignored (for example, all the activities that concerned the movement of materials and equipment such as erection of temporary platforms, installation of the rail tracks on each floor, extension of the elevators, switchboard operation, etc.). The activities were ordered from that performed on the highest floor where work was done to that performed on the lowest floor. On that day, work was done from the 60th floor (structural steel erection) through to the second basement, where they worked on the electrical finishes. Where activities were performed simultaneously on the same floor by the same subcontractor, they were grouped together. For example, connecting the beams, riveting the joints, and painting the beams were grouped in one activity; another example is the activities of constructing the formwork and fixing the reinforcement for the arched floor slabs. The resulting 28 activities are listed in Table 1.

Next, the correct work location zones were identified for each activity. Some of the activities, such as the steel erection, were performed on a zone consisting of two floors (called a "*tier*" in the original plan). Others, such as the caulking between steel trim and stone, were performed on five floors at a time. The dependencies between the tasks and delays required between them were deduced from the references and basic engineering knowledge of the logical sequence of construction activities. This yielded a

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Table 1. Activities Used for Reconstruction of the ESB Construction Schedule

Activity code	Task description	Activity code	Task description
A	Steel erection	L	Damp-proofing coat on walls
B	Steel connections and paintings	M	Windows glazing
C	Setting brackets in elevators, fire line installation, and sleeve installation	N	Setting terra cotta tiles
		O	Radiators installation
D	Form and reinforce floor arches	P	Concrete slab—elevator, motor room
E	Pouring concrete arches		
F	Stripping floor arch forms	Q	Covering steam branches
E′	Exterior metal trim	R	Outlets and underfloor ducts
E″	Aluminum spandrels	S	Lathing and plastering
F′	Plumbing	U	Floor fill and finishes
G	High tensions electrical cables	V	Lathing ceilings and walls
H	Mine hoists	V′	Finish coat
K	Patch floor arches, fireproof wind braces	W	Ducts
I	Exterior limestone walls	X	Air filter system
J	Caulking between steel trim, stone, and window frames	Y	Electrical finishes

basic flowchart of the process for a single floor with the logical order as shown in Fig. 2.

The schedule of that floor was then extrapolated to the whole building to get a draft schedule over the 86 floors. To do this, a number of anchor dates were identified from the references. The first was the "start date" of the first activity of the project as it was scheduled, the structural steel erection, which was planned to begin on April 1, 1930. Then, as a first pass, a constant production rate was assumed for all the activities over the whole project, equal to the construction rate of the structural steel erection (i.e., approximately 2 days per floor). A first line-of-balance schedule was thus compiled using location-based scheduling software.

The next step was to establish the detailed production rates for the activities, as the assumption of constant and equal rates was not supported by dates established from the historical record. Three adaptations were necessary: (1) adjust the number of working hours per week for different trades to fine-tune production rates; (2) apply slower rates where multiple teams performed work in parallel (in leapfrog fashion); and (3) introduce presumed planned time buffers. The first modification was correction of the production rate of the structural steel to the exact number of 1.8 days per floor (in fact 3.6 days per tier), assuming a 6-day working week. The second change was to recognize that different rates were set for each of the four activities that lead the project and set the construction pace for the others. These four activities, called "pacemakers" at that time (Willis and Friedman 1998), were the structural steel erection, the concrete floor arch construction, the exterior metal trim and aluminum spandrels, and the exterior limestone. The idea to set the pace originates from flow considerations in mass production; the basic time unit for the rhythm is commonly called "takt" time (Hopp and Spearman 1996). The activities are thus grouped into four streams, each led by a pacemaker activity, as shown in Fig. 2.

The third change concerns buffering, a concept that enables decoupling tasks in production systems to absorb the negative effects on succeeding tasks of variability in preceding tasks. The short overall schedule demanded for the construction of the ESB, and supposing the influence of mass production ideas among the planners of the time, raised the hypothesis that planners may have inserted time buffers in the master plan in order to shield vulnerable activities and make them as stable as possible. The most likely candidates are the pacemaker activities. To check this, the degree of vulnerability of each activity to variability was checked by considering the conditions for smooth flow listed by Koskela (Koskela 2000), assuming finish-start scheduling with no buffers. Each activity was assessed in terms of: (1) its degree of dependence on each precondition and (2) the risk of the precondition not being fulfilled. The dependence scale was: no dependence (0),

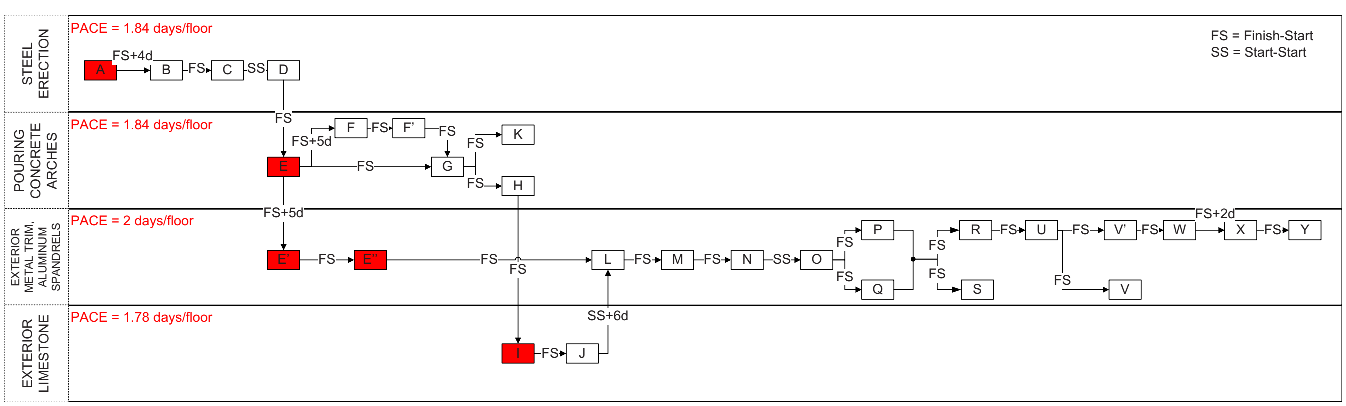

Fig. 2. Logical order of the tasks for the construction of the ESB. Takt activities are shown shaded.

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Table 2. Stability Analysis of Activities according to Seven Preconditions for Smooth Flow (Koskela 2000) in Descending Order

Activity	Previous work			Space			Crews			Materials			Equipment			Information			External conditions			Average potential instability
E′	*3*	2	**6**	*2*	1	**2**	*3*	1	**3**	*3*	2	**6**	*3*	1	**3**	*2*	2	**4**	*3*	1	**3**	**3.86**
E″	*3*	2	**6**	*2*	1	**2**	*3*	1	**3**	*3*	2	**6**	*3*	1	**3**	*2*	2	**4**	*3*	1	**3**	**3.86**
I	*3*	2	**6**	*2*	2	**4**	*2*	1	**2**	*3*	2	**6**	*1*	1	**1**	*2*	2	**4**	*3*	1	**3**	**3.71**
E	*3*	2	**6**	*3*	1	**3**	*3*	1	**3**	*3*	1	**3**	*3*	1	**3**	*2*	2	**4**	*3*	1	**3**	**3.57**
M	*3*	2	**6**	*1*	1	**1**	*2*	1	**2**	*3*	2	**6**	*3*	1	**3**	*2*	2	**4**	*3*	1	**3**	**3.57**
B	*3*	2	**6**	*2*	1	**2**	*2*	1	**2**	*2*	1	**2**	*3*	1	**3**	*2*	2	**4**	*3*	1	**3**	3.14
…																						—
Q	*1*	2	**2**	*2*	2	**4**	*2*	1	**2**	*1*	1	**1**	*1*	1	**1**	*1*	2	**2**	*0*	1	**0**	1.71
K	*1*	1	**1**	*2*	1	**2**	*2*	1	**2**	*2*	1	**2**	*1*	1	**1**	*1*	2	**2**	*1*	1	**1**	1.57
V′	*1*	2	**2**	*1*	2	**2**	*2*	1	**2**	*1*	1	**1**	*1*	1	**1**	*1*	2	**2**	*1*	1	**1**	1.57
V	*1*	2	**2**	*1*	2	**2**	*2*	1	**2**	*1*	1	**1**	*1*	1	**1**	*1*	2	**2**	*0*	1	**0**	1.43

Note: The three values for each precondition are the degree of dependence on the flow (italics), the risk of a problem occurring, and their product (Bold).

low dependence (1), medium (2), and high (3); the risk scale was: no risk (0), low (1), medium (2), and high (3). The average of the product of dependence and risk over the seven flows is a crude measure of the potential instability of the activity (i.e., the potential for problems with execution of the activity as planned).

The results are given in Table 2 (activities with midrange values are omitted for brevity). The five most vulnerable activities were: pouring concrete arches (E), exterior metal trim (E′), aluminum spandrels (E″), exterior limestone walls (I), and windows glazing (M). Of these, three are "pacemaker" activities [the first pacemaker activity (A) has high stability because it has no previous work and space is available]. This strengthened the assumption that time buffers were consciously inserted before the pacemaker tasks. Buffers were thus inserted in the reconstructed schedule before each pacemaker activity, and they were sized by trial and error to fit the dates known for these activities. The reconstructed schedule then showed very good agreement with the historical record. Table 3 details the comparison of the dates found in the references and the dates calculated from the reconstituted line-of-balance chart.

The last step was to identify those tasks that took longer on each floor than the base takt rate. These were made to conform to the line-of-balance principle by allocating multiple teams to perform them on multiple floors in parallel. The team sizes, the number of crews in which they were organized, and the "batch" sizes in terms of number of floors, were all recorded in the daily log of August 13, 1930. The final result was the full line-of-balance chart shown in Fig. 3.

Analyzing the ESB project according to the flow view of the TFV approach highlights a number of features of the production system that were carefully planned by the project management to ensure smooth flow. The following paragraphs identify the flow characteristics for each of the seven principle preconditions listed

Table 3. Comparison of the Dates from the References and Dates Calculated from the Reconstituted Line-of-Balance Schedule

	Reference data				Reconstituted line-of-balance schedule			
Activity	Start date	End date	Duration (days)	Rate (days/floor)	Start date	End date	Duration (days)	Rate (days/floor)
A	April 2, 1930	October 4, 1930	160	1.84	April 2, 1930	October 4, 1930	160	1.84
B					April 11, 1930	October 15, 1930	160	1.84
C and D					April 18, 1930	October 22, 1930	160	1.84
E		October 10, 1930		1.84	April 28, 1930	November 1, 1930	160	1.84
F					May 7, 1930	November 10, 1930	160	1.84
E′ and E″		December 1, 1930		2.00	May 12, 1930	December 1, 1930	174	2.00
F′					May 12, 1930	November 15, 1930	160	1.84
G					May 18, 1930	November 21, 1930	160	1.84
H and K					May 21, 1930	November 23, 1930	160	1.84
I	June 5, 1930	December 1, 1930	155	1.78	June 5, 1930	December 1, 1930	155	1.78
J					June 12, 1930	December 7, 1930	155	1.78
L					June 20, 1930	December 18, 1930	155	1.78
…	…	…	…	…	…	…	…	…
V′					August 3, 1930	February 27, 1931	176	2.02
W					August 15, 1930	March 10, 1931	174	2.00
X					August 24, 1930	March 20, 1931	174	2.00
Y		April 1, 1931[a]			September 1, 1930	March 22, 1931	174	2.00

Note: L to U are omitted for sake of brevity.

[a]Estimated based on project completion date of May 1, 1931.

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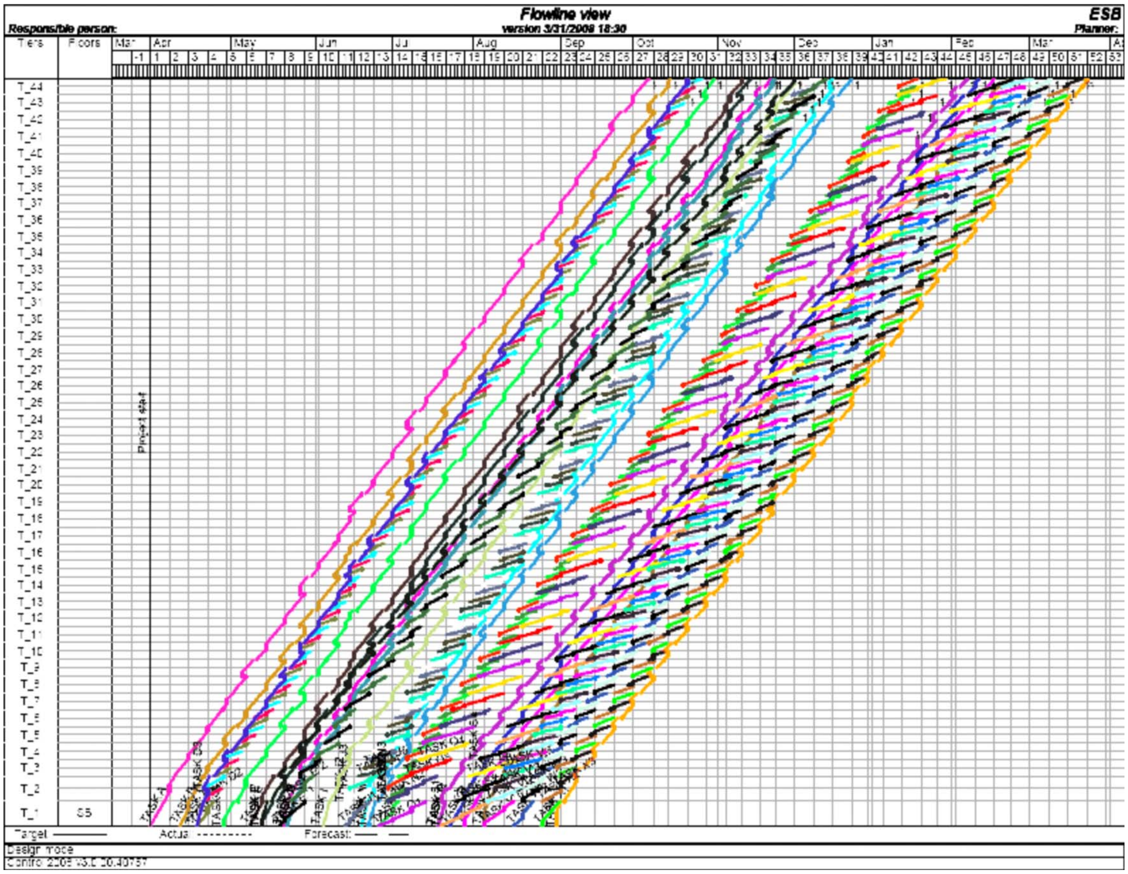

Fig. 3. Reconstituted "as-scheduled" line of balance chart for the ESB project, shown from Tier 1 to Tier 44 (88th floor). A flow view of production in the ESB project.

by Koskela (2000): information, preceding work, materials, equipment, crew, space, and external conditions.

Information Flow

A collaborative colocated team was assembled for architectural, structural, mechanical, and production design. This made the cycle of information exchange between disciplines short, enabling rapid decision making and response to mistakes in the design or incompatibility between the design and the reality of the construction site (Tauranac 1995). Concurrent design and colocation have more recently been highlighted as enablers of lean construction (Trebilcock 2004), as has the importance of small batches and short cycle times for information delivery (Freire and Alarcon 2002).

An important feature of the building's design that ensured low rates of design error and thus smooth work flow was its extreme simplicity. Existing technologies were used as far as possible in order to avoid the uncertainty of innovative methods. The designers' goal was to minimize variety and complexity. The design used a well known physical structural system (structural steel frame with arched reinforced concrete floors) and exterior metal trim and limestone for the facades, and there were very few different floor layouts.

The pull flow of structural steel, described next, extended upstream into the design and fabrication process, regulating the flow of information: designers worked from the bottom up and designed and detailed several floors at a time. Structural design drawings were furnished to the steelmakers just-in-time to allow fabrication detailing; fabrication in turn started only a few hours after the receipt of the drawings so as to supply the site only a few days later. "There were days when the messenger reached Pittsburgh with drawings only one hour before the steel mills started rolling the I beams we would need a few days later" (Tauranac 1995).

Work Flow

The use of four carefully controlled pacemaker tasks with time and space buffers between the four activity groups that they led was understood and carefully applied. These ideas largely disappeared from construction management practice with increased use of the critical-path method and the decline of production management in favor of contract management (Koskela and Howell 2002; Sacks and Goldin 2007).

Material Flow

The arrival on-site of both bulk and prefabricated materials was precisely planned. Unloading and distribution of materials was considered as an assembly line of standard parts, which had to "keep moving with a continuous feed of materials to the men" (Willis and Friedman 1998). The objective was to move the materials only once and to reduce the time between the arrival of the materials and their actual use on-site to a minimum—generally within 3 days. The production control department surveyed the various quantities put in place on-site daily. Bulk materials were essentially pulled: the challenge was to calculate the material

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buffers precisely in order to have enough materials to cope with the pace of construction but not too much because of the lack of storage space. The "Bedell System," an innovative communication technology, was used for the first time in construction to signal for material deliveries to the floors using the electric material hoists.

Special provisions were made to ensure smooth flow of prefabricated "made-to-order materials." Reliability of supply for some key materials, such as structural steel, was achieved by procuring them from more than one supplier. Off-site staging depots were used to buffer supply and enable final pull to the site. Materials were brought long distance to New York City by train and delivered to the site from freight depots by trucks. For example, steel was shipped from the shops as soon as it was fabricated and stored in the Pennsylvania Railroad yards at Greenville, New Jersey. From there, the steel was lightered to a wharf on the North River and trucked to the site as required (Willis and Friedman 1998). The pull flow also extended to pulling of design information for fabrication, as described earlier. The concept of "reverse logistics," which concerns all the operations for removing waste (Mossman 2007), was applied. A dedicated shaft, with doors that could be opened to empty a wheelbarrow, was provided for disposal of the debris produced during the construction. It ended in a direct feed into trucks parked in a bay under the building.

Flow of People

With some 3,500 people moving through the building on peak days, their transport was critical. The temporary elevator system was as efficient as the permanent elevators would be, with cars serving different zones and with zones of express service. The start and finish times for work were staggered for different trades. At the beginning of the working day, guides were stationed at the elevator entrances at various relay points and were responsible for directing the traffic of workers through the elevator system. Five temporary food stands were set up through the height of the building to minimize traffic at lunch times.

Flow of Equipment

With the exception of the concrete and mortar batching plants, all of the heavy equipment used was for transport of materials. Nine derricks were provided for lifting structural steel and two were dedicated for lifting large machinery. Their operation was kept entirely separate from that of the 17 hoists that were used to lift all other materials within the structure. This meant that there was some redundancy in vertical transport, but also that the structural and finishing operations did not impact on one another. Horizontal transport was provided by four overhead monorail trolley systems for unloading materials on the main floor and narrow-gauge industrial railway systems for distributing materials in hopper cars, with a complete loop on each floor. Transport systems were always extended at night to ensure uninterrupted service for the following working day. The designers of the production system clearly understood that vertical and horizontal delivery systems could be a bottleneck that would slow the pace of construction.

Availability of Space

Space conflicts are a significant concern in scheduling construction operations, since activities can require exclusive use of space beyond that of their immediate execution. Modern project managers have software tools that have been developed for space planning (Akinci et al. 2002). In the ESB project, just-in-time deliveries for most materials were used to avoid storage and double handling. While the stable flow of work that was achieved helped maintain the separation of teams in nonoverlapping work zones, avoiding the delays and lowered productivity that often result from interference between teams was made easier by the fact that the open space on each floor was not partitioned.

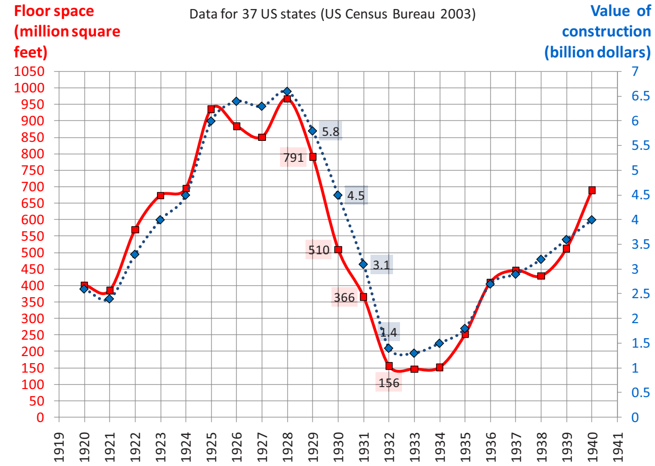

Fig. 4. Building space and value constructed in the United States from 1920 to 1940

External Conditions

The project's management succeeded in preventing disruption of the project by external conditions such as weather, regulations, and the economic crisis of the time. They avoided weather issues by enclosing the building before the advent of severe weather. Structural steel erection was completed in September, concrete construction in October, and the exterior limestone backed up with bricks was finished in mid-November (Willis and Friedman 1998). This was critical because the laws of the time prohibited work while exposed to rain, snow or high winds.

Labor and equipment were in plentiful supply because construction volumes had fallen sharply. Data from the U.S. Census Bureau for the period 1920–1940 (Census 2009), shown in Fig. 4, highlight the decrease in construction volume and of construction value added from the beginning of the ESB project in 1929 and through the whole construction period. Paradoxically, this was the best period to construct the world's tallest building. It should also be noted, however, that the historic record shows that the same general contractor completed similar buildings before the advent of the Great Depression at similar rates. In 1928 a construction speed record was achieved at 6.5 weeks for erecting a 27-story structure. In the same year, a 35 story building was enclosed in 7 months. In 1929 the Bank of Manhattan, a 77-story building, was completed in less than 1 year from the beginning of the foundations (Tauranac 1995). Thus the record rate was not anomalous, but a progression from construction experience accumulated before the Great Depression.

The project's management understood that good relationships on the project and with those living and working in its vicinity would avoid issues arising that might have impeded its progress. They established the "Empire State Building Club" to facilitate

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open dialogue among all actors within the project, and the "Fifth Avenue Association," to provide a forum for the project's neighbors.

Craft, Industrial, Mass, and Lean Construction

Until the industrial revolution, construction, like production of other goods, was almost exclusively craft production, in which all parts were hand made and unique. In manufacturing, the progression from craft to mass production is commonly illustrated by the evolution of the car manufacturing industry (Liker 2003; Ohno 1988; Womack et al. 1991). In craft production, parts were unique hand-made products of high quality, and cars were customized to each particular customer. However, damaged parts were hard to replace and productivity was low. At the beginning of the 20th century, Ford and others implemented mass production, in which cars in production flowed continuously along an assembly line (Taylor 1911). Parts were standardized and machines replaced hand-made fabrication methods. However, the ability to customize products was lost. Many of the ills of mass production (waste, overproduction, long cycle times, etc.) were redressed with the development of the Toyota Production System (TPS), which has become a model for lean production systems. Where Henry Ford saw efficiency, Taiichi Ohno saw various forms of waste. Lean production emphasizes smooth and small batch flow with little inventory of work-in-process, short cycle times, and the ability to respond to changes in the products a market demands.

In the construction industry, the progression of production systems has been different. Despite the differences between the two industries and their products, transfers of expertise between industrial sectors suggest that the progression of construction systems can be explained in relation to production systems in the car industry (Gann 1996). Craft construction originated from the pre-industrial age and embodied practices which result in custom-built construction according to owners' requirements. Even when a row of similar or identical houses was built, there were variations in each due to the methods deployed. Craft workers developed skills including knowledge of materials and manual dexterity to perform the specific tasks (Gann 2000). The 19th century was a period of rapid changes with the introduction of industrialized techniques of construction. The realization of industrialized construction was supported by the introduction of new materials and the development of special equipment to transport and erect the prefabricated elements. Between the 1950s and 1970s, prefabrication flourished in construction of social housing in many countries (Warszawski 1990). Industrialized construction focused on producing selected components off-site and failed to meet fragmented and diversified demand. Conventional wisdom suggests that the next evolutionary step was lean construction, which applied the lean thinking embodied in the TPS to identify the wastes in construction and propose a new project-oriented management approach (Ballard 2000a). In lean construction, emphasis is placed on smooth and stable flow of work, where work crews rather than products move. Low levels of WIP, short cycle times, and careful sizing and placement of buffers are additional key concepts.

However, there seems to be a gap in this continuum. After all, the importance of smooth product flow and reducing product variation were well understood in mass production systems; they were not new in lean production. At the same time, industrialized construction cannot be considered the construction parallel of mass production; rather than changing the practices on-site in fundamental ways, it was focused on moving production from sites to factories. We propose that another production system is missing in the production systems theory in construction: *mass construction*. The analysis of the processes set in place for the ESB project leads us to suggest that this system exists in application but has not previously been identified in theoretical discussion.

The construction system of the ESB had many mass production features, such as the adoption of scientific management with monitored controls (Taylor 1911), the production of high volumes of standardized products with a high production rate, the breaking of processes into small fragments, the mechanization of standardized tasks with high volumes, and the creation of a moving and nonstop assembly line. For example, elements—such as metal spandrels, windows frames, and stones—were standardized as much as possible to reduce the time of installation and to enable subdivision of tasks into smaller subassemblies (Willis and Friedman 1998). Material transportation was also designed as a mass production process: materials were brought to workers in order to reduce the workers' movements on-site. Another idea, prominent in Ford's system, was to impose the production rate on the works and to adjust teams to meet the same rate at each workstation. The concept was applied on the Empire State project by the introduction of the four pacemaker tasks. Work on-site was also supported by off-site fabrication. These features highlight the importance of the influence of Ford's concepts on the conscious design of the production system set in place for the ESB.

Thus the definition of mass construction as a building production system could be characterized by the following features:

- Multiple uniform and repeated spaces or modules;
- Work flow planned using takt time (pacemaker tasks);
- Industrial supply chain management;
- Monitoring and control of production rates;
- Carefully designed logistic systems to deliver materials;
- Standardized work;
- Minimal variety of parts; and
- Careful control of tolerances between parts.

In practice, both industrialized and mass construction approaches are employed in parallel in tall building construction, for different building systems. Also, aspects of craft construction persist throughout, coexisting with mass construction. Unlike in other industries such as car production, old processes are not completely swept away from one system to another. Traditional and modern processes coexist side-by-side (Gann 2000). In the ESB, numerous trades remained essentially craft activities with no industrialization, hand made and executed by a large number of skilled workers, but being performed within the logistic framework of mass construction (examples are bricklaying, tiling, plastering, lathing, setting marble, waterproofing, and caulking).

Interestingly, some of the concepts and practices that are typically associated with lean construction are identified in the Empire State project, such as:

- Concurrent design of process and product by collaborative teams;
- Standardized design of components and work procedures;
- Scheduling according to takt time;
- Judicious use of time buffers to shield downstream work from activities identified as having high variation;
- Pull flow of materials with effective delivery systems;
- Decoupling at off-site staging areas for prefabricated and other materials (sometimes termed "consolidation centers"); and
- Minimizing of worker travel by provision of all facilities.

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Table 4. Key Characteristics of Four Different Construction Systems

System characteristics	Craft construction	Industrialized construction	Mass construction	Lean construction
Nature of the building products	Unique components and unique spaces	Uniform components	Uniform components and uniform repeated spaces	Customized spaces
Labor	High-skilled trades	Low skilled but highly specialized	Specialized trades with narrow focus	Multiskilled teams
Flow system	No consideration of flow	Push flow—discontinuous flow	Continuous flow (stable due to uniformity of products)	Pull flow
Batch sizes	Small batches	Large batches	Large batches	Small batches
Inventories	Small inventories	Large inventories of components	Large inventories of components off-site, large inventories of spaces	Small inventories
Logistics	No logistics system	Off-site materials logistics system	On-site materials logistics system	On-site and off-site logistics system for all resources

Table 4 summarizes the key characteristics of the four different construction systems. A key difference between mass and lean construction is the inability of mass construction to cope with variation in the building design, as opposed to lean construction's adaptability for customized buildings and spaces.

Conclusions

Since the time of its completion, the record rate of construction achieved in the ESB construction project has not been surpassed, and indeed the average construction rate for tall office/commercial buildings appears to be declining. The greater complexity of modern buildings, in terms of the number of interrelated systems that must be installed in them, is clearly part of the explanation for this. Nevertheless, analysis of the ESB project as an exemplar for the management of tall office/commercial buildings at that time, under the microscope afforded by modern production concepts, enables a deeper understanding of the project and the reasons for its success, and of modern approaches to construction.

The reconstructed schedule of the project reveals planning that consciously considered the flow of work. The production planners set time buffers to shield tasks from variability, they used stable pacemaker tasks to set the pace for all activities, and they sized work teams and work zones to fit whole multiples of the base takt rate in order to achieve balanced production rates for all activities in each paced group. While it is true that the economic circumstances of the Great Depression provided stable supplies of workers, equipment, and materials, the same contractor had achieved similar construction rates in other projects before the advent of the economic depression.

The analysis of the project as a network of interacting flows shows that management concepts that had not yet been identified explicitly in the context of construction were nevertheless applied in practice on the project and resulted in a successful and efficient construction process. The collaborative design team represents an important innovation for the time and implies low variation in design, continuous small batch information flows and short cycle times for dealing with errors. The investments in logistic resources with multiple parallel paths made the project stable, preventing bottlenecks in the supply chains. Sophisticated buffers, such as consolidation centers, complemented with a pull system for delivery to site, enabled limiting material storage on-site, moving material once only, and ensured a continuous work flow.

The production system of the Empire State project is identified as a mass construction system. Mass construction has not been identified previously in construction theory, which has focused on craft, industrialized, and lean construction. Introduction of the term mass construction helps explain the evolution of production systems in the construction industry; it fills a gap in the continuum of construction system development. The recent ideas of lean construction are then seen as a progression from craft, mass, and industrialized construction. One of the challenges for application of lean construction is to identify the right methods to cope with an industry that has not evolved from craft to mass construction, but one that remains mixed between them. From the perspective of research toward a theory of production in construction, it is important to recognize the complexity that the mix of craft, industrialized, mass, and lean practices in any modern project brings to the problem. Similarly, construction managers may be better able to assess and ameliorate variability in their systems, and to design better production systems for their projects, if they recognize that most construction projects mix flows that have the characteristics of these four types.

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