

Cranes for Building Construction Projects

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Abstract: Cranes have come to symbolize building construction itself. They perform indispensable services in moving materials and components vertically and horizontally. Used since antiquity, their history is interrelated with the development of new power sources that replaced man and mule, first steam and later internal combustion, diesel, and electric engines. Mobile cranes can be rapidly deployed to lift heavy loads. New models with telescoping booms and all-terrain travel capability, compact urban machines, and even hybrids with tower cranes are beginning to replace the familiar lattice boom truck cranes. Mobile cranes have dominated the North American market, but a cultural change appears to be taking place toward tower cranes for building projects. Tower cranes, common in Europe for decades, are globally gaining in popularity with surging real estate developments. Ideal for dense urban environments and coming with a small footprint, they are available in a growing diversity of sizes and configurations. Sophisticated electronic controls and operator assistance devices are enhancing their safe and productive operation. While cranes occupy a central role on midrise and high-rise building projects, they operate in conjunction with other types of supporting equipment that are an essential part of the overall equipment array on today's industrialized construction sites.

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Introduction

Today's building construction projects are highly mechanized and becoming more so every day. With the growing industrialization of construction, there is a shift to offsite prefabrication of structural and finish elements that are then installed or assembled rather than produced on site. Consequently, production equipment is being replaced on the construction site by *transportation* equipment. Material handling and lifting equipment now dominates building construction sites more than ever before and constitutes the critical element in achieving productivity.

The typical building construction site will employ several or all of the following equipment types: (1) cranes; (2) material handlers; (3) concrete pumps; (4) hoists and lifts; and (5) forming systems. Concrete is commonly produced on site only in the case of large projects requiring high concrete volumes, or when transportation distances are too great for the supply of ready-mixed concrete. Earthmoving equipment is used for the initial, substructure phase of building construction, but is hardly seen on the

jobsite throughout construction of the structure itself.

Of the above-listed equipment types, *cranes* are the most conspicuous machines on site, owing not only to their size but also to the vital role they have in transporting materials and elements vertically and horizontally. When selecting equipment for a project, cranes are the centerpiece of the selection process and decisions made on the selection and location of cranes commonly govern the selection of other equipment.

The construction industry in North America has traditionally been a *mobile-crane* culture (Shapira and Glascock 1996) with the number of mobile cranes in the United States being far greater than the number of *tower cranes*. However, tower cranes, the icon of construction in Europe and the industrialized Far East, are increasingly found on United States building sites. While mobile cranes are nonetheless by and large the backbone of the United States construction industry, the demand for tower cranes on the part of American contractors is rising. Crane rental companies have responded to that demand by increasing the share of tower cranes in their fleets (Bishop 2000, 2001; Shiffler 2006b). High-rise construction has always been dominated by tower cranes, but these machines are now often seen on midrise and low-rise building projects as well. This is particularly true for buildings having a concrete structural frame. The type of work and the long service durations of a building project plus space-constricted sites that cannot accommodate mobile cranes are pressures that drive the utilization of tower cranes.

Equipment offered and used for building construction has seen other changes in recent years. Most notable is the abundance of telescopic-boom handlers used for moving materials and workers about the jobsite. Modern telescopic materials handlers—*telehandlers*—are replacing traditional forklifts. Coming with a variety of front-end attachments, these machines are gradually taking over for other equipment, such as backhoe-loaders and small rough-terrain mobile cranes (cherry pickers). Telescopic aerial work platforms and scissor-type lifts are often used on tasks for which conventional scaffolds were commonly erected in the

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past. Often a great number of these and other light, versatile, mobile units may be seen on just one construction site. Forming systems are an integral part of today's on-site equipment for concrete building construction. Forming systems have undergone significant modernization in recent years, one major direction of this modernization being industrialization to modular components. *Mechanized* forming systems in cast-in-place concrete building construction, however, are available for specialized uses only.

This paper presents the current status of cranes for building projects, as these are usually the controlling construction machines on such projects. The paper opens with a short history of building construction equipment. It then focuses on cranes and reviews their various types, mainly with respect to current design and configuration trends, as well as technology advancements. Next follow observations about the cultural changes in North America regarding cranes, then possible drivers for these changes are suggested. The concluding part addresses several other equipment types and their interrelationships with cranes on today's construction sites.

Short History of Building Construction Equipment

"I am accustomed, most of all at night, when the agitation of my soul fills me with cares, and I seek relief from these bitter worries and sad thoughts, to think about and construct in my mind some unheard-of machine to move and carry weights, making it possible to create great and wonderful things" (Alberti 1441). King (2000) discusses this sentence in his book on Filippo Brunelleschi's dome (of the Basilica di Santa Maria del Fiore in Florence), which was built without wooden falsework, and explains how the speaker, the famous Renaissance scholar Leon Battista Alberti, is fantasizing about machines to aid in constructing monumental buildings. Builders have always dreamed of better machines to make the tasks of moving, lifting, and fitting building parts together easier. The builders of monuments, public buildings, and residential structures in antiquity found ways to erect their structures using only sledges, wheeled carts, and crude scaffolds. Today engineers and tourists marvel at and admire historic structures around the world and wonder how the builders accomplish such works without our modern machines. The pyramids in Egypt, Mexico, and Peru or the great aqueducts of the ancient Romans were constructed with none of the diesel powered, hydraulics controlled, energy enhancing machines used today to erect buildings.

Equipment for building construction has a rich and varied history that predates most other types of machinery. Roman architect and engineer Marcus Vitruvius Pollio, who lived in the first century B.C., described in the tenth book of his *De Architectura* the state-of-the-art in mechanical contrivances, going back to Greek roots. These included winches and pulleys for hoisting; levers and fulcrums; wagons and carts; buckets, water wheels, and pumps; and the famous Archimedean water screw (Morgan 1960). The first cranes consisted of derricks with large tread wheels. Roman semicircular arches and domes were erected on elaborate wooden falsework, e.g., the Pont du Gard in France and the Pantheon in Rome, which were built from 27 to 25 B.C.

Master builders in medieval Europe oversaw complex construction sites that in the case of cathedrals often required more than 100 years to complete. The Master Builders' responsibility spanned architecture, engineering, and construction aspects, including devising the means and methods of construction and organizing the logistics for the work. Their notebooks and illumi-

nations found in medieval manuscripts give an account of the rich technology they developed. Medieval mechanical accomplishments drew on the previously described ancient machines. Tread wheel and winch cranes were also found being used for loading and unloading medieval merchant ships. Water wheels, pumps, and shoring were applied in mining for iron ore and some precious metals throughout medieval Europe (Rae and Volti 2001) and in the 1800s were used in the growing number of shipping canal and water supply systems projects (Kirby and Laurson 1932).

Throughout the ages, there has been the fundamental need for building construction equipment to provide means of *amplifying* the power (Schexnayder and David 2002) and *extending* the reach of the individual laborer on a construction site. Machines lead to immense increases in productivity (Goodrum and Haas 2004). In the historical overview, the pulley had already allowed manifold multiplication of the human power. Yet early cranes were still limited in their horizontal reach, no truly mobile machinery existed, and muscle power of the horse, mule, or man, along with waterpower remained the primary driving engine for these machines.

The major breakthrough for building construction equipment was the development in the 1700s of the steam engine, which was initially used to drive the factories of the Industrial Revolution. The first piece of construction equipment to use this new power source was the steam shovel, invented by William S. Otis in 1835 (Schexnayder and David 2002). Steam shovels were developed and originally used by contractors on the expanding railroad system in the United States. But they soon found employment during the final stages of excavating the Suez Canal and then as the main stay for excavating the Panama Canal (Larkin and Wood 1975). The internal combustion engine arrived with the early automobile, invented in 1885 by Karl F. Benz. This new power source was soon incorporated into trucks, which essentially were conceived as enlarged motorized versions of the wheelbarrow. Rudolf C. K. Diesel in 1892 invented the rugged engine type with compression ignition named after him, which has since become the major power type for construction equipment.

Building construction in the 20th century saw numerous noteworthy projects where innovative equipment solutions were deployed successfully. The riveted structural steel frame of the Empire State Building was erected in only 410 days (i.e., less than 14 months) from 1930 to 1931. It retained the title of the tallest building in the world for more than forty years. Large derrick cranes were used to lift the steel columns and beams. "Lifting steel more than thirty stories in one motion was not practical, so a series of relay derricks were built on [the building's] setbacks or on platforms built out from the edge of the building. Depending on how high the building had risen, the steel would be transferred directly to the erection derricks, or to the relay derricks and finally to the erection derricks" (Tauranac 1995). The speed of construction reportedly averaged 4.5 stories per week (Willis 1998). Delivery of materials occurred via railroad from the factories in New Jersey to the barges that then hauled the steel across the Hudson River to the New York wharfs where it was loaded on trucks. Advances in hoisting equipment together with highly standardized mass-produced structural elements not only allowed for fast assembly with highly repetitive mechanized operations but also brought about a very low accident rate for the large numbers of workers on the project.

When the *Journal of Construction Engineering and Management* was launched in 1957, then called the *Journal of the Construction Division*, the Empire State Building had been in place

Table 1. Site and Equipment Management Papers in the *Journal of Construction Engineering and Management*, 1983–2000 (Adapted from Pietroforte and Stefani 2004)

	1983–1985	1986–1988	1989–1991	1992–1994	1995–1997	1998–2000	1983–2000
Number of site and equipment management papers	10	16	18	21	16	17	98
Overall number of papers	107	143	138	162	163	179	892
Percent of site and equipment management papers	9.3	11.2	13.0	13.0	9.8	9.6	11.0

for 26 years. That monumental building was followed by many other great achievements worldwide that demonstrated the continuing development of the construction industry and its equipment. Equipment papers published in the *Journal* throughout its 50 years, however, have focused mainly on equipment for civil or heavy construction rather than on building construction equipment. These papers have discussed a wide range of topics, including equipment selection, operation, management, economics, productivity, safety, valuation, and replacement.

The history of equipment for earthmoving operations and the anticipation for future developments were well documented in a series of three papers in the year of the Golden hard hat—the 50th anniversary of the Construction Division (Larkin and Wood 1975; Klump 1975; Douglas 1975). Two decades later, Arditi et al. (1997) reviewed innovations in construction equipment, and more recently, a fourth paper was added to the 1975 series in 2002 to celebrate the 150th anniversary of the society. That paper by Schexnayder and David (2002) updated many of the notions raised almost three decades earlier. Most recently, another pair of papers (Tatum et al. 2006a,b) examined the historical development of earthmoving equipment technology from a systems point of view.

Pietroforte and Stefani (2004) reported on the types and numbers of scholarly publications in the *Journal of Construction Engineering and Management* from 1983 to 2000. Table 1 shows the overall number of papers that were categorized by Pietroforte and Stefani under *site and equipment management*. It is noted that these publications predominantly examine heavy equipment for civil and earthmoving operations. A noteworthy example of exception is a paper on equipment economics for building construction (Selinger 1983). Papers concerning cranes—both mobile and tower cranes—quite naturally made up the majority of *building construction equipment* papers, given the centrality of cranes in building construction operations. Interestingly, papers on topics considered by many as construction equipment (e.g., formwork and shoring, concrete placement) were counted by Pietroforte and Stefani under a separate category, *construction methods and materials*, and are therefore not reflected in the data provided by Table 1. Overall, Table 1 shows that equipment papers, as categorized by Pietroforte and Stefani, make up about 11% of papers in the *Journal*.

Crane Types

Construction cranes are classified into two major families of machines: tower cranes and mobile cranes. In some regions, including North America, the term “mobile cranes” is often used to refer to *truck-mounted* mobile cranes only, while *track-mounted* mobile cranes are then considered a separate family, referred to as “crawler cranes.” Some machines are a marriage of tower and

mobile crane types, attempting to achieve the advantages of the two forms. An example of such a hybrid crane is the truck-mounted bottom-slewing tower crane, an old concept that has seen a renaissance in recent years. Offered by tower crane manufacturers (or the tower-crane division of manufacturers of both tower and mobile cranes), this is essentially a tower crane (in both horizontal reach and lifting capacity) with the mobility of a mobile truck crane. An opposite example is a new “telescoping mobile crane” prototype machine soon to be offered by one mobile-crane manufacturer (Keßel 2007). Here the design challenge is the high lifting capacity and short setup time of a mobile crane combined with a tower-crane’s vertical (though not horizontal) reach.

Using the word “family” in this text implies that there are great many different equipment types and configurations under each one of these two terms, tower cranes and mobile cranes. The lack of universally accepted classification and taxonomy for cranes attests too to the great variety of very different but in some cases very similar types that carry a different classification. This lack of standard classification often leads to confusion when discussing cranes.

Tower Cranes

Tower cranes, essentially in the same configuration as we know them today, became conspicuous in the late 1940s when they helped rebuild Europe after World War II. These are small-footprint machines powered electrically for noiseless operation and suitable for tight urban construction sites of both low- and high-rise structures. Over the years, the tower crane has seen enormous developments in terms of reach and lifting capacity, as well as improvements addressing deployment and operational convenience issues. A tower crane is suitable for a wide range of work assignments and site conditions, and responds to the great variety of needs and preferences of construction firms and crane rental companies. Its operating and control systems have undergone major changes using the technological developments of our times. This is also true for its safety features. Although the electrically powered tower crane is still the most common model, diesel-powered models are available particularly in North America.

In high-rise construction, tower cranes may provide the only solution for lifting materials, building elements, and formwork components (other than concrete, which can also be and indeed is often pumped). However, in many parts of the world, particularly in Europe, tower cranes are widely used for all kinds of building projects, urban and rural. Additionally, they are found on civil infrastructure projects. Lightweight, fast-erecting models are the machine of choice for the construction of low-rise residential and commercial structures, and even one-story houses in France, Italy,

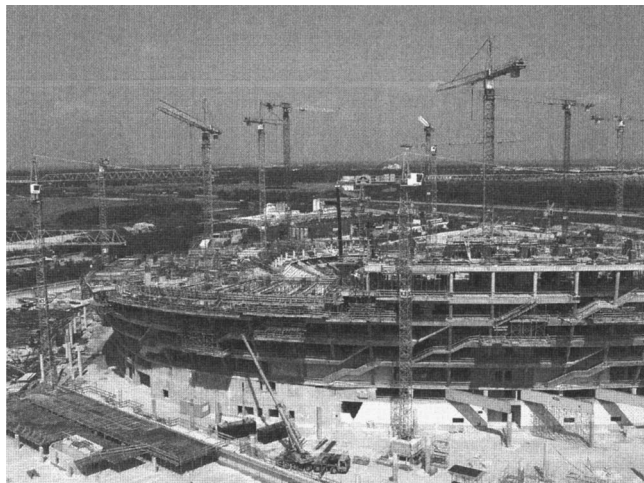


Fig. 1. Multicrane construction site (Allianz Arena stadium, Munich, Germany, 2003; Photograph by Israel Mizrahi, Israel)

Germany, and Switzerland. In recent years, these lighter models have begun to show a modest but growing and noticeable presence in North America on a variety of projects where traditionally mobile cranes would have been employed (Bishop 2004; Shiffler 2006a).

Tower crane “forests” have been conspicuous in recent years in many places: in Berlin, as the reunified Germany built its new capital in the late 1990s; in the Chinese city of Shanghai, and then in Beijing in preparation for the 2008 Olympic Games; and for the unparalleled surge of office, condominium and hotel complexes under construction in the United Arab Emirates in the mid 2000s. Even in the United States the increasing use of tower cranes has recently caused many cities to be dubbed “Crane City.” In Miami alone 300 tower cranes were estimated to have been working at one point in 2006 (Shiffler 2006b).

Because tower cranes can be mounted on rails, a *traveling* tower crane had traditionally been a common way to obtain a larger work envelope and better site coverage, whenever site conditions enabled installing a railway. This solution permitted the elimination of at least one additional crane, as long as lifting requirements in terms of service time could be accommodated by only one crane. This situation is not, however, typical on today’s construction sites. The competitive nature of construction and the high priority given to meeting tight deadlines for handing over the completed building often overshadow the relative cost of placing additional cranes on a project. Furthermore, with the increasing industrialization of construction sites, cranes are now busy providing lift services for a variety of elements and in frequencies far surpassing the requirements of the past. Demands on crane time have thus increased dramatically. Consequently, cranes are often utilized to their full capacity each workday and in many instances night shifts must be incorporated into the schedule in order to meet all lifting requirements placed on a crane.

In many cases one crane cannot provide, time-wise, all lifting services required within its reach envelope. The result is a growing number of multicrane sites (see Fig. 1), as well as a greater sharing of work zones, created by overlapping crane envelopes. This, in turn, has driven other recent developments such as the increased use of *flat-top* tower cranes and the growing demand for advanced anticollision systems.

There are two main types of tower cranes, *top-* and *bottom-slewing*. The major differences between these two types are re-

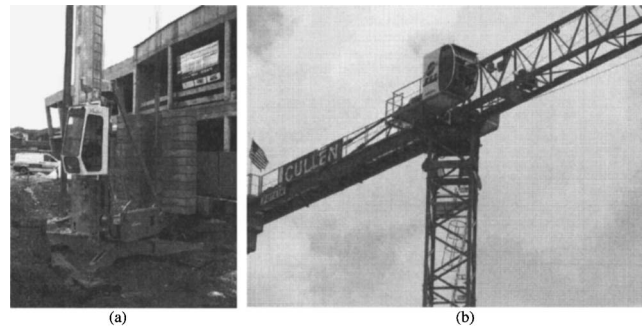


Fig. 2. Operator cabs for tower cranes: (a) bottom-slewing crane; (b) top-slewing crane (photograph by Dr. Aviad Shapira)

flected in erection and dismantling operations for each and in their maximum mast height. Erection and dismantling of bottom-slewing cranes are relatively simple and rapid, earning these cranes the nicknames *self-* and *fast-erecting* (the latter, however, should not be confused with the same term often used by manufacturers to describe certain models of top-slewing cranes). This ability, however, comes at the expense of height. Top-slewing cranes, on the other hand, take much longer to erect and dismantle. Their erecting and dismantling are complicated and costly operations but their mast can reach 300 or more meters. In the case of a tower crane that climbs on the building frame as construction proceeds, mast height is relatively short, but dismantling such a crane from the top of a high-rise building poses an operational challenge and is particularly costly. Given these characteristics, bottom-slewing tower cranes are suitable mainly for short-term service durations on low-rise projects, while top-slewing tower cranes are better suited for high-rise projects requiring long service periods.

Tower-crane masts commonly have an open lattice design (see Fig. 1). Lattice-type masts of top-slewing tower cranes are assembled from modular sections; hence the term “sectional tower crane” is often used in referring to top-slewing cranes. Bottom-slewing tower cranes commonly have a *telescopic* lattice-type mast, earning these cranes the name “telescopic tower crane.” In recent years, however, manufacturers have developed closed tubular (hollow) section masts for bottom-slewing cranes. Initially this was only for the small models but increasingly hollow-section masts are found on larger models. On the smaller models, the hollow-section mast is often foldable instead of telescopic. Fig. 2(a) shows the lower part of a hollow-section mast of a bottom-slewing tower crane. Note the climbing operator cab, a new feature that serves as an operator elevator and at the same time allows movement of the cab along the mast such that operator view is optimal.

Climbing operator cabs on *top-*slewing cranes are a more difficult design challenge because, unlike with bottom-slewing cranes, the mast of the top-slewing crane is fixed and the cab must be made to revolve with the crane’s jib. On the other hand, climbing a top-slewing crane is usually more of an issue due to the crane’s greater mast height. Therefore, a separate operator elevator is more common with these cranes than climbing cabs. There are, nevertheless, special climbing cabs available that rotate around the mast in synchronization with the slewing jib. Operator elevators have been mandated in several European countries for top-slewing cranes where climbing height exceeds 25–30 m. Such elevators, however, have not yet gained wide usage outside statutory countries in Europe.



Fig. 3. Top-slewing luffing-jib tower cranes (Las Vegas, 2006) (photograph by Dr. Aviad Shapira)

Because the top-slewing crane's cab is almost always located at the top of the mast, often at a great distance from the load and work arena, there is a greater importance to improving operator's sight quality on this crane type. Therefore, modern cabs have an operator sight-oriented design with a large glass panel area [Fig. 2(b)], which allows better vision of the site affording greater control of rigging and hook movement. Along with other features that improve the operator's ergonomic work environment, this design supports safer and more productive work. Note that both top- and bottom-slewing tower cranes can be controlled remotely. However, this feature is common mostly with bottom-slewing cranes and they often come without an operator's cab.

The horizontal *saddle jib*, known as a "hammer head," is the most common, top-slewing tower crane type though cranes with other jib configurations are available. *Flat-top* cranes, also nicknamed "topless," have a pendant-free, cantilever jib connected only to the mast [see Fig. 2(b)]. By eliminating the upper structure above the jib of the crane, the "cathead," these cranes are particularly suitable for a shared-zone multicrane environment, where overlapping crane jibs must swing at different heights. Because a safety clearance must be maintained between the uppermost part of the lower crane and the jib bottom of the upper crane, the entire height of the cathead-frame, which could be as much as 14 m, is saved when using flat-top cranes. This reduces the required mast height of the upper crane. Furthermore, this is an advantage in other situations where height restrictions apply, such as near airports. Flat-top cranes have become very popular regardless of such constraints, due mainly to their ease of setup. They now constitute a growing percentage of tower-crane fleets in the United States.

Both saddle-jib and flat-top jib cranes use a trolley that travels ("trolleys") along the jib, carrying the hook block of the crane. By means of the trolley, the horizontal reach of the crane is varied. These two types of top-slewing cranes are therefore often referred to as "trolley-jib cranes." Another jib configuration is the *luffing jib* (Fig. 3). Top-slewing cranes of this type, nicknamed "luffers,"

do not use trolleys but rather change their horizontal operating reach or radius by raising and lowering the jib. The term "luff" comes from sailing ships and refers to the spar holding out the windward tack of a square sail. Many luffing-jib crane models feature a very short counterjib; along with the luffing capability, it may be an advantage when the crane operates in proximity to other cranes or obstacles (such as adjacent buildings). These cranes, therefore, are often used in high-density urban construction. A cantilevered *moving-counterweight* system for luffing-jib cranes, introduced several decades ago, appears to have regained some interest recently. This mechanism increases the distance between the counterweight and the mast as the jib is lowered (i.e., the reach is increased) and thereby reduces the difference between the two moments. The counterbalancing thus causes less stress to be placed on the crane's structure. The two luffers in Fig. 3 are fitted with moving counterweights.

Mobile Cranes

Unlike the tower crane, which is essentially a stationary machine, the mobile crane, as its name implies, is a self-propelled mobile machine, capable of moving freely about the jobsite and in the case of many such machines between jobsites as well. Contrary to the tower crane's silhouette of a vertical mast with a horizontal jib at its top, the mobile crane's jib, termed the "boom," is inclined and connected directly to the machine's carriage. If the variety of tower crane types appears to be prodigious, mobile cranes feature even more types and models. The span of machine size ranges from mini-machines fitting in the back of a small truck to gigantic models that dwarf almost any other piece of construction equipment.

Mobile cranes owe their extensive use in North America to the ambitious heavy civil and infrastructure projects launched in the early and mid-20th century (Shapiro and Shapiro 1988). In part, their development is tied to the development of agricultural machinery. Agricultural machines were the incubator for many types of heavy construction equipment in the United States (Haycraft 2002). Among other things, this has contributed to the great versatility of mobile cranes, which are equally associated with non-building operations, such as excavation and pile driving. Even today, these machines find their main use in a variety of civil engineering projects other than building construction. Some mobile cranes types, however, have a significant presence on building construction sites, whether for short-term tasks or throughout the duration of a project's construction. In the United States, *crawler* mobile cranes are still extensively used on building construction projects, whether alongside tower cranes or as the sole lifting service providers (Fig. 4).

Mobile cranes are the machines that set up the tower cranes at the onset of construction and dismantle them at the conclusion of their service on site. This is a classic demonstration of the mobile crane's main features: its capacity to be rapidly deployed and to handle heavy loads. A relatively small mobile crane has a lifting capacity equal to that of a heavy tower crane. The largest mobile cranes, though taking longer to deploy, can lift 1,000 tons or more.

When discussing equipment for building projects, it is important to note that concrete building construction typically involves extensive *duty-cycle* work, namely, work in which the crane is engaged in repetitive lifts of relatively short cycle time. Handling a bucket for concrete placing is a typical example of such work. While tower cranes inherently are suitable for duty-cycle work,

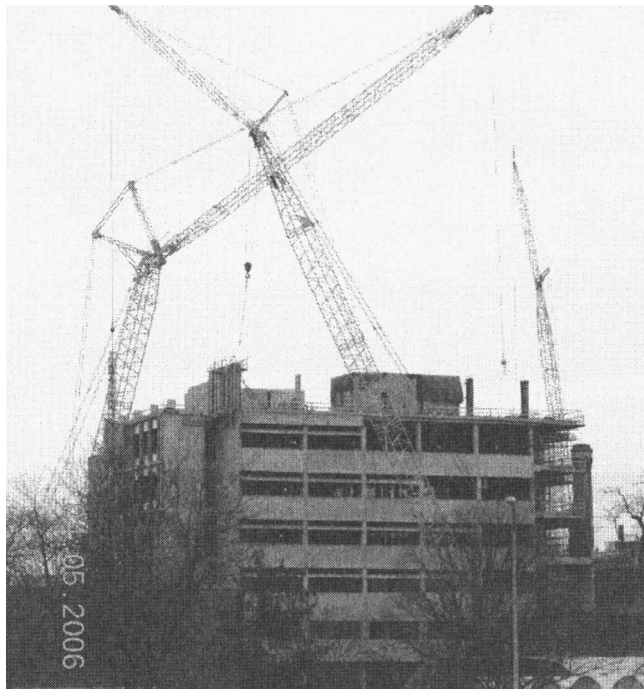


Fig. 4. Mobile cranes on a midrise cast-in-place concrete construction project (Madison, Wis., 2006) (photograph by Dr. Aviad Shapira)

mobile cranes are not, unless the drums are equipped with a special lagging. Because the loads involved in cast-in-place concrete building construction are relatively light compared to lifting large structural components, mobile cranes of various types that are fitted for duty-cycle work are commonly of the small to mid-sized models.

Several developments in mobile crane configuration, made possible by advanced technologies and stemming from demand, have been perceptible in recent years. Most noticeable is the growing use of *telescopic booms*, which facilitate far more rapid crane deployment than would be the case with lattice-boom cranes and which allow boom length to be changed in the course of work. Telescopic boom length, typically limited by boom weight, has increased as well, owing mainly to modern boom-section design and high-strength lightweight steels. Nonetheless, lattice booms provide any given lift requirement at a lower cost and are still much in use. Lattice-boom cranes are those used when lift requirements exceed the maximum possible with telescopic booms. Additionally, lattice booms are used extensively as boom extension on telescopic-boom cranes.

One outcome of the growing popularity of telescopic booms is the introduction of the telescopic-boom crawler crane, a rare combination until only a few years ago. This machine appears to be an appropriate option for a growing number of uses. Although production of these machines is still limited and they are truly a specialty machine in terms of application, more and more models of this machine are being offered by manufacturers. The telescopic crawler crane combines the advantage of the crawler undercarriage, specifically jobsite maneuverability and outrigger-free work, with the advantages of the telescopic boom. One example of a good application is on city streets where contact pressure with the street surface is restricted due to underground infrastructure. Wheeled cranes with outriggers may not be suitable where these restrictions exist, while a *rubber-crawler*

telescopic-boom crane provides a solution. This solution has found widespread use in Japan.

Lattice-boom *truck cranes* are gradually making room for telescopic-boom truck cranes. This is the result of the greater flexibility offered by the telescopic boom in deployment on the project site. Traveling on the road at high speeds is made possible by the crane's special undercarriage and is the truck-crane's most distinct capacity. The number of truck-crane models offered by manufacturers is however decreasing. This is the result of the growing popularity of *all-terrain cranes*, initially in Europe and more recently in North America (Shapiro et al. 2000). However, truck cranes, both lattice- and telescopic-boom, appear to be maintaining their standing as a viable option when no particularly rough-terrain site conditions need to be accommodated. This is mainly due to their lower cost compared to all-terrain cranes and their ability to travel the public highway system essentially like any other truck.

A different style of truck crane has recently appeared on the market. Nicknamed the "city crane" and featuring a compact design, lower boom mounting, and a single dual-purpose (truck and crane) operator cab, it is designated mainly for urban work and travel.

Arguably the most visible mobile crane on a great variety of construction sites is the *rough-terrain* crane. As implied by their name, these are designed mainly for lifting work on sites having rough ground conditions and where frequent on-site relocations are necessary. The world over, the smaller models of the rough-terrain crane are used as high-mobility auxiliary equipment on building sites that employ tower cranes as the central providers of lifting services.

The *all-terrain* crane, a relative newcomer to North America, opts to combine the best of truck and rough-terrain crane features. The number of models offered by manufacturers is growing in response to the worldwide demand for these telescopic-boom cranes. Tilting operator cabs have become standard on new models. Such cabs improve operator view and increase operation efficiency while preventing neck strain. In terms of technology and features, all-terrain cranes are perhaps the most advanced and sophisticated mobile cranes offered today, which also accounts for their high price and, consequently, to the high lifting cost per unit tonnage involved.

Electronic Age

Developments in computerization and communication have not bypassed the world of construction equipment. Today's cranes are "electronically loaded," as reflected in all of the crane's systems: drives, controls, transmissions, monitoring, and communication. Whether standard or optional, various advanced technology features aim at enhancing crane work productivity and safety. A multitude of auxiliary systems is offered by both crane manufacturers and the crane peripheral industry to support crane selection and operation, as well as equipment maintenance and fleet management. Many of the systems are an integral part of new cranes only, while others can be fitted onto used cranes as well, thereby upgrading their operation (Rosenfeld and Shapira 1998).

Three types of developments are mentioned here, to demonstrate the abundance of systems available.

Selection Software

Advanced graphics software packages are available for dealing with the "hard" technical and engineering aspects of crane selec-

tion and location, as well as lift planning. As a minimum, they serve as structured checklists of site and machine parameters that have to be considered. However, their main benefit is in their facility to check a great number of alternatives instantly. Some of the packages feature crane databases containing built-in dimensions and capacities of common equipment models by various manufacturers. Most packages handle mobile cranes only, but some accommodate tower cranes as well (Meehan 2005).

Camera Systems

Lifting operations involving work zones or travel paths concealed from the operator's vision, often termed "blind lifts," are common in both tower and mobile crane work. The world over the use of signalers is the common solution to this problem. A safe blind lift cannot practically be performed without a signaler or several using hand signs or radio communication or both. In many countries, at least one signaler is statutorily mandated on any project site that has a crane deployed. However, many crane-related accidents are attributed wholly or partly to faulty signaling, stemming from various problems (e.g., high worker turnover, inadequate signaler training, and language barriers to name but a few).

Crane-mounted video camera systems, available in recent years for both tower and mobile cranes, help overcome most of the safety issues associated with blind lifts. They can also increase crane work productivity due to speedier work and shorter cycle times. The camera, installed on the tower crane's trolley or the mobile crane's boom-end, is permanently directed downwards at the work scene, with the lifting hook constantly located at the center of the image. The video image of the load and its immediate surroundings is transmitted, via wireless communication, to a monitor located in the operator cab (Howes 2005).

Anticollision Systems

Combining hardware and software, anticollision systems are designed to prevent collisions of tower cranes operating in shared work zones. Shared zones are a common safety hazard on construction sites employing more than one tower crane. The anticollision systems use wireless communication and other technologies to monitor the crane's movements in real time; warnings are followed by automatically slowing the crane's motion and, eventually, by forcing a complete stop. Most anticollision systems feature the ability to prevent collisions with adjacent buildings and other obstacles, such as power lines, as well as to prevent slewing and trolleying over areas defined as "prohibited zones," such as busy streets and public buildings. Because of these added features, the systems are useful on single-crane sites. Due to the fairly high price of these systems on the one hand, and the traditional tendency of construction firms to adhere to "tried and true" practices on the other hand, these systems have so far found their use almost solely on multicrane projects. There are signs, however, that appreciation for the system is growing and construction firms are opting to use the systems even on sites with a small number of cranes.

Culture Change?

In the early 1990s, the metropolitan Albuquerque area in New Mexico, with a population exceeding 600,000, was experiencing an unprecedented construction boom (Odenwald 1993; Building boom continues 1994). There was the mammoth construction site

for a new Intel plant in Rio Rancho, as well as the construction of various facilities at Kirtland Air Force Base. Given the number and complexity of projects around Albuquerque, a visitor to the city, versed in the European construction culture, would have expected to see the skyline dotted with tower cranes. Nevertheless, at that time, only two tower cranes were to be found operating on projects in the area and only one of those was owned by a local contracting firm; the other crane at the Intel site had come with an out of state contractor. This reality prompted research into crane usage in the southwestern United States and the United States in general. That research identified and analyzed the practice of using mobile cranes in the United States for building work and coined the term "mobile crane culture" (Shapira and Glascock 1996).

Some 13 years later, in Madison, Wis., a much smaller city, population 230,000, where strict zoning regulations limit the construction of high-rise buildings, there were more than a dozen tower cranes working on various construction sites in March 2006. Over a period of twelve months, more than *two* dozen tower cranes were observed operating in downtown Madison and at the University of Wisconsin-Madison campus. When Madison celebrated its 150th birthday, a local weekly posted a picture of one of the many construction sites in town, with the caption, "Madison's official city bird: the crane" (Madison 150 2006).

It is important to emphasize that in both cases, the buildings that were constructed and served by cranes were similar in dimensions. In Madison, these projects were not the type of buildings for which a tower crane is the only possible lifting solution. Yet, the preferred solution found in 1993 for project execution in Albuquerque was the mobile crane whereas in 2006 tower cranes ruled in Madison.

Apparently there has been change in how contractors select cranes for building projects. Is this an industry-wide cultural change? Not all changes are long lasting, and culture changes in particular are difficult to assess without a long-term time perspective. The uncertainty regarding the intensity and endurance of the change notwithstanding, there may be factors that speak not merely for a change, but indeed for a *culture* change. Although it would take a thorough study to verify these factors as change accelerators, they may be laid out here as a departure point for further study.

When studying the culture of using mobile cranes, one of the major findings of Shapira and Glascock (1996) was that the existing mobile crane culture nurtured itself. Namely, while there were factors responsible for the *development* of the mobile crane culture, there were also factors *maintaining* the culture. These latter factors, which serve as a barrier to change, were primarily the existing mobile crane infrastructure, including: (1) availability of machines and services; (2) knowledge and expertise; (3) technical support; and (4) dealer distribution networks. There was no similar supporting infrastructure with respect to tower cranes within the three states studied (Arizona, Colorado, and New Mexico). The Shapira and Glascock study involved 36 construction sites with projects being built by 29 different construction companies and interviews with dozens of construction professionals (project managers, superintendents, engineers, subcontractors, managers of crane rental companies, and crane operators).

This crane "culture" situation and the opportunities it offered were apparently comprehended and addressed by the leading American mobile crane manufacturers. Through increasing globalization processes they have gradually become more aware of the European equipment culture. Most notably (but not solely), Manitowoc, a major American mobile crane manufacturer, iden-

Table 2. Estimated Number of Tower Cranes

Country	Year estimated	Tower cranes	Population (million) (10 ⁶)	Comments	Reference
United Kingdom	2004/2005	1,500	60	1,000 TS; 500 BS	Red Revival (2004) Skinner et al. (2006)
Spain	2006	5,000	40	TS and BS	Greeman (2003) Bishop (2006)
Italy	2003	5,000	60	TS and BS	Dalrymple (2003)
Germany	1998	45,000 ^a	83	8,000 TS; 37,000 BS	Strecker and Moldenhauer (1997) Germany Focus (1998)

Note: TS=top-slewing tower crane, BS=bottom-slewing tower crane.

^aThis figure is the peak number during the reunification-related construction boom. The number has dropped considerably after the boom was over in the early 2000s (Bishop 2005).

tified the potential of creating a tower-crane infrastructure in North America using its existing nationwide organizational and distribution network. In 2001, Manitowoc acquired Potain of France, arguably the world's largest tower cranes manufacturer, with about one third of the world market (Potain's progress 2000). [Liebherr of Germany is the other major tower-crane manufacturer, claiming also to hold about one third of the world market (Brüstle 2000); Liebherr distributes its tower cranes in the United States through Morrow.] Three years earlier, Terex, a U.S.-based global construction equipment manufacturer, acquired two smaller, albeit well known, worldwide tower cranes manufacturing companies, Comedil of Italy and Peiner of Germany.

The fact of the matter is that the number of tower cranes in the United States, long estimated to be steady at 800 to 1,000 units (Bishop 2001; Hampton 2004), started growing from the time of these acquisitions, namely, the late 1990s to early 2000s. No firm statistics are available; yet, judging by various indicators, including recent acquisitions by crane rental companies, there may be currently (2007) as many as 1,500 tower cranes in the United States and as many as 2,000 units in the entire North America region (personal communication, Glen Tellock, President, Manitowoc Crane Group, January 26, 2007). The vast majority of these cranes are of the top-slewing type.

Impressive as this growth may be, these numbers are still modest by any European standard, both in absolute terms and much more so when considering the United States population of 300 million (see Table 2). These numbers do, however, show the great potential for the tower-crane market in the United States.

It appears, then, that these companies, by their acquisitions and the subsequent promotion of tower cranes (Bishop 2001), have not only responded to the growing demand for tower cranes but have further cultivated and increased the demand. In fact, this process, joined by other market players riding on the wave of the renewed interest in tower cranes, has created new demands for tower cranes, of various other makes as well. In short, the acquisitions that reflected and even predicted a changing pattern were also a stimulus to the change.

It should be stressed that this development and the aforementioned impressive growth in numbers, apparently the result of this development, may have been aided by the increase in high-rise building construction across the United States. Nonetheless, there is little doubt that this change would have taken place, though maybe more slowly. This assertion is supported by the reality that in the United States tower cranes are nowadays favored, to a growing extent, for midrise and low-rise building projects that were traditionally constructed with mobile cranes. Additionally, there is the penetration of the smaller bottom-slewing crane mod-

els, even for civil infrastructure projects, into the U.S. market. While it thus appears that mobile cranes of all types are maintaining their standing as major lift service providers for many project types, we may be witnessing a culture change, in which tower cranes are replacing mobile cranes for building projects and also increasing their presence on other types of projects.

Other Equipment for Building Construction

Cranes do not operate in a void. The selection and employment of a particular crane for a project is strongly interconnected with and is often a driver in the selection and employment of other equipment on a building project.

Telehandlers (see Fig. 5) are a vital machine on most building sites today. Whether serving low-rise and midrise buildings or even multistory building projects, they offload delivery trucks and place materials directly on the lower floors, thereby reducing the workload of the cranes. Their role becomes even more important when stationary tower cranes are the main service providers on the site. The telehandler is today's classic multipurpose machine owing to its high mobility, versatility, and horizontal and vertical reach. The increased popularity of telehandlers can be attributed to their usefulness on industrial and construction sites alike, as well as to the increasing use of packaged materials that are delivered to the site on pallets. With a variety of front-end attachments



Fig. 5. Typical telehandler (photograph by Dr. Aviad Shapira)

easily and quickly interchanged, telehandlers can be configured not only as forklifts but also as cranes, front loaders, access platforms, or for handling concrete buckets. The rapidly evolving telehandler market is causing manufacturers to offer a great many models featuring reach and capacity ranges that keep increasing. While the telehandlers of the 1980s were able to serve up to three-story high buildings, (Selinger and Shapira 1987), mid-2000s telehandlers can reach up to the ninth floor level of a building. Some of the largest machines available today are not much different in size and capacity from small rough-terrain “cherry picker” cranes that they have replaced.

Concrete pumps are increasingly used in lieu of cranes for moving concrete vertically and horizontally on building sites. These single-purpose machines offer much higher placing rates than cranes; additionally they free the multipurpose cranes to provide lifting services that are impossible with other equipment. Furthermore, with their ability to place concrete in confined spaces that are inaccessible to cranes, pumps offer greater flexibility in scheduling project work (e.g., concrete can be placed in the basement or ground floor after construction has progressed to the upper floors of the building). Truck-mounted pumps (“boom pumps”), featuring up to 60 m in reach and eliminating the need for pipelines, can be the sole means for concrete placing on many types of projects. Easily mobilized and rapidly deployed on site, they often solve the problem of placing concrete outside the work envelope of the stationary tower crane. Line pumps with climbing placing booms—sometimes more than one—can be seen today on almost any high-rise building site (two booms are discernible on the roof of the concrete structure in Fig. 3). Although tower cranes on high-rise construction are often fitted with special high-speed motors to reduce hoisting time, they can never match the outputs possible with high-end concrete pumps (Peurifoy et al. 2006).

Self-propelled *aerial work platforms* (“boom lifts”), fitted with either a telescopic (“straight”) or articulated (“knuckle”) boom, are classified mainly by their size. Common maximum vertical reach is in the range of 10–40 m, but some telescopic models extend as high as 50 m. Common maximum horizontal reach is 6–20 m, and 25 m maximum for the largest-size models. Other than reach, machines differ from each other in terms of maneuverability in various surface conditions, dimensions and ability to move through narrow paths and operate in confined spaces, and platform size. Manufacturers offer a variety of standard and optional features that are likely to be used by the workers performing their job from the platform. Examples are electrical outlets and air lines on the platform, as well as integrated generators with electric, air, and water lines running through the boom to the platform to power a variety of tools (Hindman 2005).

Self-climbing forming systems for walls and other vertical building elements are useful when crane time is at a premium. Commonly seen only on high-rise buildings of 30 stories and higher, such forming systems save crane time and may even eliminate the need to bring an additional crane to the project site. Unlike cranes, which are prone to work stoppage due to hazardous winds, particularly when lifting large-size form panels that act like a sail in the wind, these mechanized, crane-independent systems can continue to operate in high winds. Coupled with system-integral weather protection means, this ability enables the self-climbing system to maintain its work pace irrespective of the weather. Self-climbing (or automatic climbing) systems can accommodate horizontal elements, such as connecting slabs. Furthermore, these systems are not limited to only forming building cores. They are often used for the entire vertical enclosure of the

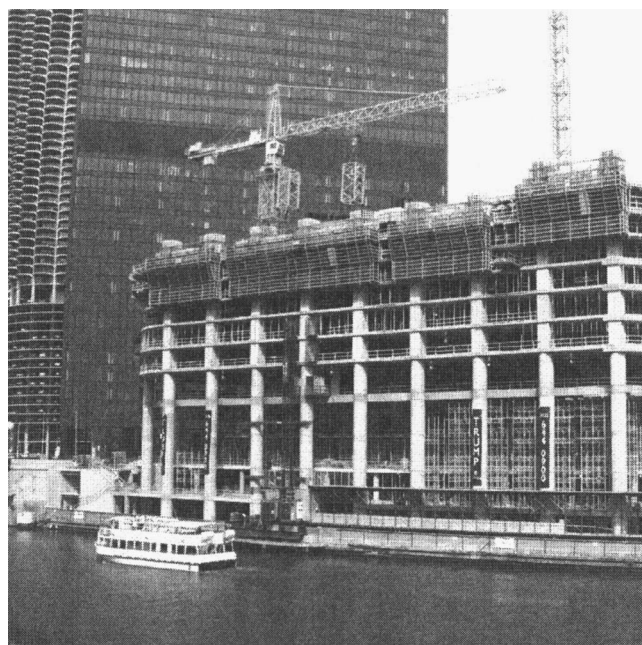


Fig. 6. Crane-independent self-climbing forming system (Trump Tower, Chicago, 2006) (photograph by Dr. Aviad Shapira)

floors, offering integral solutions for column and beam formwork, and customizable for almost any facade design. Some systems feature provisions for hanging the vertical forming panels such that work on the floor slab (formwork, rebar, concrete placing) can progress uninterrupted by the climbing system, and vice versa. Unlike the vertical *slipform*, which is maintained attached to the fresh concrete throughout its continuous sliding, the self-climbing form retracts from the hardened concrete wall before climbing to the next level (building floor). The climbing rails and other load-carrying components of the hydraulic mechanism are supported on the hardened walls of the lower level. If a climbing tower crane and/or concrete placing boom are used, their climbing masts (and the pump’s running pipeline) can be integrated in the climbing system as well. A recent notable example of this system’s use is the Trump Tower in downtown Chicago (Fig. 6) that is currently under construction. When completed, this 92-story building will be the tallest reinforced concrete building in the United States (McHugh 2005; Baker et al. 2006). Also seen in Fig. 6 are the two tower cranes serving the building (not seen is the concrete placing boom). The crane on the left side was in the midst of self-raising operation when this picture was taken.

Conclusion

The increasing industrialization of building construction, the nature of duty-cycle concrete construction work, and the required sequencing in constructing a concrete-frame building, all accord certain advantages to using tower rather than mobile cranes on midrise and high-rise building construction sites. These advantages, however, have been known for years, yet in the United States the growth in tower crane popularity began less than a decade ago.

The writers arrived at the conclusion that, similar to the findings of the 1993–1994 study of mobile-crane practices (Shapira and Glascock 1996), now, too, the causes for the change and its timing originate in a set of external and non-project-specific fac-

tors. These factors are shaping the construction culture. It took several decades for the mobile-crane culture described by Shapira and Glascock in the mid-1990s to develop and mature. It, therefore, remains to be seen whether the identified change will be similarly strengthened. There are global issues external per se to the construction industry, which are exerting considerable influence on this matter and which support the likelihood that the change will endure and even intensify. Such concerns are the increasing costs of energy and growing awareness of environmental issues, which provide further advantages to using electrically powered machines such as tower cranes.

The abundance of high-rise construction witnessed in recent years is likely to continue in the near future, given the continuing prevalence of the factors that have driven this trend. Tower cranes will thus be further in demand. In the event that the current surge of high-rise real estate development subsides, as may eventually happen, there will be tower cranes available for reuse at attractive prices. Mobile cranes, however, will maintain their dominance on a multitude of projects—other than buildings—that they excel in servicing and continue to perform specialized lifting tasks—on all kinds of projects—that tower cranes cannot perform.

As a concluding remark, attention is redirected to two papers referenced earlier, Shapiro and Shapiro (1988) and Shapira and Glascock (1996). Shapiro and Shapiro, the acclaimed crane authorities, presented in their paper a review of the construction crane types used at the time. Addressing primarily a North American readership, the paper did not even mention bottom-slewing tower cranes though this was a comprehensive and detailed paper. It is interesting to note that merely two decades ago, these machines were a nonentity on the American construction scene.

The other paper, by Shapira and Glascock (1996), provided insights on the decision drivers that shape and maintain a certain equipment culture. Globalization was merely beginning to flourish in 1993–1994, when that study was conducted, yet the paper advocated the consideration of such drivers on the part of construction companies operating overseas, often in a scene different than at home. At the same time, and while tower cranes were hardly used in the United States unless project and site conditions left no other choice, the paper encouraged construction companies operating in the United States to consider the potential gains of employing tower instead of mobile cranes on particular projects. Based on the findings of that study as well as on familiarity with the tower crane world, the paper arrived at the conclusion that companies pioneering in the use of tower cranes on projects that otherwise would employ mobile cranes may attain a significant edge in the then tight and intensely competitive building construction market. That conclusion was reinforced by the handful of such cases encountered while conducting that study.

Judging by what is happening today, it appears as if those recommendations have indeed been followed. Furthermore, the conditions that drove the recommendations, both globally and at home, prevail today in even greater intensities. Fortified by the changing crane infrastructure, these recommendations can therefore be more strongly reiterated.

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