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Characteristics of Equipment Planning for Multi-Crane Building Construction Sites

Aviad Shapira * and Albert Ben-David

Faculty of Civil and Environmental Engineering, Technion–Israel Institute of Technology, Haifa 3200003, Israel; abd@barak.net.il

* Correspondence: avishap@technion.ac.il; Tel.: +972-54-447-4963

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Abstract: This paper purports to provide answers to the following questions with regard to multi-crane building construction sites: (1) Do such construction sites differ from smaller sites only in magnitude, or are there *unique* characteristics that stem from the size of the site and the multitude of cranes? (2) Is equipment planning for such projects similar to that of projects serviced by a small number of cranes? (3) How is equipment planning affected by the site's surroundings? (4) Does the visibility of multiple cranes in the near and far surroundings of the project affect the approach to equipment planning? Answers to these questions were sought after through the investigation of several measures, based on case studies of mega building projects in Europe, all located in busy urban surroundings. On-site interviews focused on multiple research variables, of which four are used here: project planning stages, planning parties, plan formats, and the cranes on site. The study found that multi-crane sites are characterized by unique features; equipment planning for such sites differs significantly from that conducted for regular sites; the site-surroundings interface plays an important role in equipment and logistics planning for such sites; and the awareness of reputation plays a role in crane selection. The study's main contribution is in reducing the knowledge gap that exists with regard to the unique determinants of equipment planning for multi-crane projects and to its importance to the success of such projects.

Keywords: construction; crane selection; equipment planning; mega building projects; multi-crane sites; tower cranes

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1. Introduction

Multi-crane sites offer fascinating views: five, eight or twelve tower cranes working in concert, covering the entire area of the sizable building footprint and staging areas with their multiple work envelopes, over-sailing numerous shared work zones at graded heights, and constituting the face of construction to the outside world in their protrusiveness. Do such construction sites differ from smaller sites only in magnitude, namely, "more of the same", or are there unique characteristics that stem from the size of the site and the multitude of cranes? Is equipment planning for such projects—often referred to as mega building projects—similar to that of projects serviced by no more than one, two or three cranes? How do the site's surroundings affect equipment and logistics planning for such projects? Does the visibility of the crane forest in the near and far surroundings of the project affect the approach to equipment planning and its outcome?

This paper purports to provide answers to these questions through the investigation of several measures, based on case studies of multi-crane building construction sites in Europe. The paper first presents a concise review of the literature concerning the focal issues in the current study. Then the data collection method and the measures used for analysis are presented. Next comes the main body of the paper—presentation and discussion of the characteristics of equipment planning for multi-crane sites found in the study. Finally, conclusions and recommendations for further research are offered.

2. Background

2.1. Mega Building Projects

The wide body of published research on construction megaprojects focuses almost exclusively on *infrastructure* rather than on building projects (to the point that many such publications do not even mention the word "infrastructure" in their titles). This is likely because mega infrastructure projects (1) have a larger physical, environmental and economic footprint; (2) affect a larger segment of the public; and (3) are typically affiliated with national or international development plans [1–5]. Mega building projects, on the contrary, are often perceived merely as larger "regular" projects. One noticeable indication of the exclusive focus of megaproject studies on civil and infrastructure works rather than on building construction is the fact that the debate on the definition of megaprojects essentially addresses infrastructure construction and discusses parameters and magnitudes of parameters (mainly cost and physical size) that are, for the most part, either irrelevant to building construction or far exceed values extant in building construction [6–9]. (Note that, in the present context, the term "mega building project" refers to a single building rather than to a cluster of separate buildings such as national airports, large-scale housing projects, or sports villages.) Thus, in addition to the lack of a uniform definition of megaprojects and of a characterization that distinguishes them from smaller projects, major issues that appear to be of interest to the research community with regard to megaprojects (political, social, ecological, cultural, statutory, urban, and more) are typically associated with large-scale infrastructure and development projects [10–12]. Nevertheless, although building projects differ in many respects from infrastructure projects, particularly in terms of the types of equipment used, the review of the literature on mega infrastructure projects can still shed light on several characteristics that may also be shared by mega building projects.

Of the five characteristics proposed by Fiori and Kovaka [6], only one—lofty ideals—appears to be exclusive to mega infrastructure projects and irrelevant to mega building projects of the type studied here; the other four characteristics listed are magnified cost, extreme complexity, increased risk, and high visibility—all of which are also relevant to building projects. Indeed, the last item on this list is particularly relevant to the current study, and is elaborated later on in the paper. Barakat [13] devoted a large part of his literature review to studying the characteristics of mega construction projects, focusing on grand-scale development projects with a threshold cost of US $1 billion. (While this threshold has been increasingly adopted worldwide as a criterion for megaproject definition, an alternative suggestion, which considers the great variance in the gross domestic product (GDP) in different countries, is 0.01% of the GDP) [8]. Despite the fact that the highest project cost in the current study was €500 million (~US $625 million), several of Barakat's characteristics are relevant here too, including design and construction complexity that results from risk and uncertainty, attraction of public attention, involvement of a large number of partners, and technological challenges that call for and bring about innovative solutions. Among megaproject characteristics listed by Oliomogbe and Smith [6] in a summary of a literature review, most of which are typically relevant to infrastructure projects, several features may also apply to building construction of the kind addressed by the current study: the main contractor is privately owned [12]; the project/structure is captivating because of its size, engineering achievements, or aesthetic design [14]; and the project may arouse public opposition to the likely social, economic and environmental impacts [15]. Nonetheless, the literature review conducted within the current study revealed neither characteristics *specific* to mega *building* projects nor quantitative measures by which to define them.

2.2. Equipment Planning for Multi-Crane Sites

The term "equipment planning" in the current context refers to the selection, location, and operation management of equipment for building construction; some related aspects of logistics planning are, necessarily, included as well. Tower cranes are the main piece of equipment addressed by the planning process, and their specific models and layout are the primary products of that process.

The selection of other major equipment, such as concrete pumps and forming systems, is intertwined with that of the cranes and is typically guided by the former.

The professional literature hardly ever addresses multi-crane sites, to say nothing of focusing on equipment planning. This may stem from a notion—proved incorrect in the current study—that such sites differ from smaller sites only in magnitude and not necessarily in complexity, and that no different approach to crane selection and location should therefore be developed for such sites. With the ever-increasing industrialization of construction and the acceleration of construction schedules, multi-crane sites appear to be steadily growing in number; yet, their relative scarcity may be another reason for their absence from the body of published research. Another reason for the relative disregard of multi-crane sites by the literature may be the natural focus placed in recent years, in crane-related construction planning research, on high-rise construction in which the advantages offered by tower cranes are fully realized, whereas multi-crane sites in the current sense are typically spread out and low-to-medium rise.

Focusing on productivity- and safety-driven locations of cranes, algorithms have been offered that use various advanced information technology tools to obtain optimal solutions [16–22]. These, however, commonly address only three cranes at the most—which touches on the fundamental question of how many is actually "multi" with reference to the number of cranes on site. Unlike the aforementioned studies, which use terms such as multiple, several, a set of, and a group of cranes while demonstrating the models they propose on only two or three cranes, the current study adopted a greater number of cranes as its threshold. Indeed, Wang et al. [23] exemplify their optimization model on a 12-crane site; however, theirs is not a single-building project serviced by numerous cranes, as is studied here, but rather a cluster of six buildings, each serviced by two cranes. Furthermore, all of the afore-mentioned research efforts tackle the problem from a computational-quantitative perspective with a focus on the product (crane locations, supply locations, collision-free paths, motion planning, lift scheduling), whereas the planning *process* and its determinants are of no less interest. Indeed, a qualitative perspective that gives room to often-governing soft factors may yield important aspects of equipment planning and management that the use of hard factors alone may not reveal.

3. Research Method

3.1. Case Studies

3.1.1. Projects

Data were gathered through case studies of ten multi-crane building construction projects in Europe: six in Germany, three in the United Kingdom, and one in France. Twenty projects were initially identified based on their (1) physical size (gross built area $\geq$ 50,000 m^2); (2) construction budget ($\geq$ €100 M); and (3) number of tower cranes ($\geq$ 5). Following preliminary site visits and interviews, the list of qualified projects detected was narrowed down to ten projects, after applying additional selection criteria: (4) a distinct horizontal dimension (on three of the projects: in addition to the vertical dimension); (5) under construction at the time of the study; (6) a single building constructed by a single general contractor as a single project; (7) busy urban location; and (8) willingness of the project's management to cooperate with the research team. Table 1 lists the final ten projects selected for the current study, in chronological order of their investigation. Mean (and median) values of the first three aforementioned criteria were as follows: gross built area 115,300 m^2 (104,500 m^2), construction budget €233 M (€200 M), and number of tower cranes 6.9 (5.5). As is expected from projects of such magnitude, they were all executed by well-established, leading construction companies known for their highly developed planning culture. To achieve as a broad and varied picture as possible, the ten projects that were selected were executed by eight different companies. While homogeneity was maintained in terms of project type (i.e., exclusively buildings, rather than other types of civil engineering structures or infrastructure projects), project designation included various uses such as shopping centers, office buildings, and mixed use of commercial, residential, and office projects. The number of workers per project at peak time ranged between 400 and 1,200 and the site's management, engineering and technical staff numbered between 40 and 80 persons. Thus, by any standard, these were mega building projects.

Table 1. Profile of projects.

Code	Project	Location	Contractor	Designation	Gross Built Area (m^2)	Construction Cost (Million €)	Construction Duration (Month)	Number of Tower Cranes
1-DE	Höfe am Brühl	Leipzig, Germany	Max Bögl	Shopping center	120,000	220	30	8
2-DE	Leipziger Platz	Berlin, Germany	BSS	Shopping center, hotel, residential	152,000	300	36	9
3-UK	"Walkie Talkie"	London, UK	Canary Wharf	Offices	103,000	250	38	5
4-DE	Skyline Plaza	Frankfurt, Germany	Max Bögl	Shopping center	185,000	200	28	9
5-DE	TaunusTurm	Frankfurt, Germany	Züblin	Offices, residential	103,000	200	36	5
6-UK	Trinity Leeds	Leeds, UK	Laing O'Rourke	Shopping center	100,000	200	48	5
7-UK	North East Quadrant	London, UK	M3 + Lend Lease	Commercial, residential, offices	77,000	200	33	5
8-FR	SFR Rimbaud	Saint-Denis, France	Bateg + Sicra	Offices	106,000	160	23	6
9-DE	BMBF	Berlin, Germany	BAM	Offices	57,000	100	30	5
10-DE	Milaneo	Stuttgart, Germany	Züblin	Shopping center	150,000	500	33	12

3.1.2. Cranes

Table 2 presents the profile of the 69 cranes used on the ten investigated projects. All cranes were of the top-slewing type; 50 were of the trolley-jib type and 19 had a luffing jib. Most of the 50 trolley-jib cranes were of the regular type (i.e., an upper A-frame, to the top of which the pendants holding the jib and counter-jib are anchored) and the rest were configured with a flattop (cantilevered) jib. The five largest projects in terms of the number of cranes (1-DE, 2-DE, 4-DE, 8-FR, and 10-DE)—which are also the largest in terms of gross built area (see Table 1)—were the five projects that employed a mix of regular and flattop trolley-jib cranes. Flattop cranes save crane height and therefore accommodate the requirement for graded heights on sites with multiple crane overlaps better than do regular cranes. The four projects using luffing-jib cranes were the smallest in the sample (with five cranes each), and three of them included buildings that exhibited both vertical and horizontal dimensions. No distinct pattern can be discerned regarding crane procurement: all cranes on the largest project (in terms of the number of cranes) were company-owned, while the next two largest projects employed either exclusively rented cranes or a mix of rented and company-owned cranes. Similarly, three of the six smallest projects in the sample used all rented cranes and the other three used all company-owned. Finally, while it is most common to see German-made cranes in Germany and French-made cranes in France, two of the German projects used a mix of French and German cranes, as did the sole French project in the sample. All British projects in the sample used German or Italian cranes; there are no British manufacturers of tower cranes.

Table 2. Profile of tower cranes.

Project Code	Number of Cranes						Crane Manufactureer (Number of Cranes)
	By Type			By Procurement Method		Total	
	Trolley Jib		Luffing Jib	Owned	Rented		
	Regular	Flattop					
1-DE	7	1	-	8	-	8	Liebherr (6), Potain (2)
2-DE	6	3	-	-	9	9	Wolffkran
3-UK	-	-	5	-	5	5	Wolffkran
4-DE	7	2	-	4	5	9	Liebherr (7), Potain (1), Wolffkran (1)
5-DE	-	-	5	-	5	5	Wolffkran
6-UK	-	1	4	5	-	5	Comedil
7-UK	-	-	5	-	5	5	Wolffkran
8-FR	3	3	-	6	-	6	Liebherr (3), Potain (3),
9-DE	5	-	-	5	-	5	Liebherr
10-DE	10	2	-	12	-	12	Liebherr (3), Wolffkran (9)
Total	38	12	19	40	29	69	

3.1.3. Interviews

Each case study included several phases and consisted of personal interviews, site visits, inspection of various exclusive project materials provided by the site, and completion of information by mail and phone. The core of the study comprised in-depth structured interviews—one to three per project—with the contractor's project manager and often with the participation of other senior management personnel (particularly those in charge of the site's equipment and logistics planning). These interviews, which were conducted on the construction sites, were based on an interview guide that contained both open-ended and structured questions and typically lasted three hours each; the mean cumulative duration of interviews for each project was about six hours. All principal interviewees were senior practitioners with dozens of years of experience, and with 11 to 28 years of specific experience in the managing of mega building projects (with budgets exceeding €100 M). Although most interviewees spoke English, the findings of Harzing [24] regarding the dependence of interviewee response style (and consequently also accuracy and credibility) on language were adopted, and so the interviews in Germany and France were conducted in German and French, respectively. To that end, the research team was assisted by the translation services of local engineers who were adequately briefed on the study before the interviews. Additional interviews were conducted with senior representatives of four independent firms who provided equipment and logistics planning services to several of the projects studied. These interviews served both to complete project-specific information and to gain a deeper, non-project-specific understanding of the issues treated in the current study.

3.2. *Variables*

The on-site interviews focused on multiple research variables, four of which were used in the phase of the study reported on here: (1) project planning stages; (2) planning parties; (3) plan formats; and (4) the cranes on site. Other research variables, and notably crane selection *factors*, will be addressed in later reports.

3.2.1. Project Planning Stages

Three project planning stages were distinguished between as follows [25]:

- Prebid planning (PBP): takes place prior to the submission of the bid. Its duration varies widely, from a few weeks to several months, depending mainly on the type of contract and the owner's timetable.

- Preconstruction planning (PCP): starts immediately upon the award of the contract and continues up to a certain point in the construction, typically not more than two months beyond mobilization.
- During-construction planning (DCP): starts one to two months after mobilization and lasts with varying intensities throughout the life of the project, following a repetitive pattern.

3.2.2. Planning Parties

The initial list of parties participating in equipment planning (hereby also termed "involved parties") was based on lists offered by Laufer et al. [26], who did not focus on equipment but rather addressed a whole range of construction plans, and by Shapira and Schexnayder [27], who focused on equipment planning in a mobile-crane culture. The list was then expanded and refined during the preliminary interviews conducted in the current study, to include a much higher-resolution composition of potential participants as follows: (1) owner; (2) company management (i.e., senior management at the company—not project—level; e.g., general director, chief engineer); (3) company office (i.e., technical staff at the company's home office; e.g., planning and control, operations and engineering); (4) project manager; (5) general superintendent (also termed "construction manager" or "site manager"; the common terms in Germany, where six of the ten case studies took place, are "chefpolier" or "oberpolier"); (6) project engineer; (7) company equipment manager; (8) company safety manager; (9) other project trades (i.e., other clients of crane time, typically various subcontractors); (10) crane supplier; (11) structural engineer; (12) geotechnical engineer; (13) external logistics planner; (14) public relations; and (15) authorities.

3.2.3. Planning Formats

As with the planning parties, the initial list of formats used for the issuance of equipment plans followed the list used by Laufer et al. (1993). (The aforementioned Shapira and Schexnayder [27] study did not address formats of plans after Shapira and Glascock [28] found that, in a typical mobile-crane culture, the issuance of *documented* equipment plans was the exception, not the rule.) That basic list was then expanded, in the course of the preliminary interviews, to address appropriately the expected nature of equipment planning on sites employing multiple tower cranes.

3.2.4. Cranes on Site

This variable primarily included the number of cranes, jib lengths (which determine work radiuses), heights, and location. Also addressed were crane configuration, make, color, and procurement method (i.e., company-owned or rented).

3.3. Measures

The measures and rating methods used to identify and analyze the characteristics of equipment planning in the projects investigated in the current study were as follows.

3.3.1. Involvement in Planning

The interviewees were requested to evaluate the degree of involvement of each party in the preparation of the equipment plan. The involvement was rated on a four-level scale: "high", "moderate", "low", and "not at all." This rating was determined three times, once in each project planning stage.

3.3.2. Issuance of Plans

The interviewees were requested to check the various formats used for plans issued as the documented outcome of equipment planning, in each of the three project planning stages. Interviewees received a list of suggested formats, but they were not restricted to it.

3.3.3. Features of Cranes and Crane Layouts

This measure examined the cranes and their layouts on the sites, mainly through investigation of various geometric features and their implications for crane work (as detailed later in the presentation of the characteristics themselves).

4. Findings: Equipment Planning Characteristics

4.1. Multiplicity of Involved Parties

Considerably more functional parties were involved in the equipment planning of the studied projects than are typically involved in the equipment planning of regular, non-multi-crane projects. This conclusion was not only drawn from comparisons of the current findings with those of previous studies but was also attested to by the interviewees based on their rich cumulative experience with other projects. This increase in the number of involved parties appears to be the result of project scale, complexity, and unique needs associated only with building projects of the magnitude examined here.

Mean numbers of all participating parties were computed for the PBP, PCP, and DCP stages across all projects, and were found to be 7.1, 8.7, and 7.8, respectively. These numbers reflect the entire prescribed scale of degrees of involvement. To filter for considerable involvement only and to compare results with two previous studies, mean numbers of participating parties were also calculated separately for the two upper levels on the four-level scale, namely high and moderate degrees of involvement. Results for PBP, PCP, and DCP were 4.4, 6.8, and 4.2, respectively, with an overall mean number of participating parties across all planning stages of 5.1.

Table 3 presents the profile of the current study alongside profiles of the two previous studies whose findings are examined here vis-à-vis those of the current study. Shapira and Schexnayder [27] studied equipment planning using variables and measures similar to those used in the current study, though the projects in their study were regular (i.e., not mega) building projects. The respective numbers of participating parties Shapira and Schexnayder found (Table 4) were considerably lower than those found in the current study: the overall mean number for megaprojects is 70% higher than for regular projects, and in PCP the increase—of 94%—is the highest, which really should come as no surprise. Indeed, previous studies defied the conventional notion that planning is done only before construction starts and showed how it is conducted—with changing focuses and patterns—continually throughout project life [25,26,29,30]. Nevertheless, pre-construction is still the project stage during which most planning, in its classic meaning, takes place. The current results further accentuate this conclusion with respect to megaprojects, given the complexity and wide span of interrelated planning issues involved, which appear to surface and demand detailed attention mainly during PCP.

Part of the aforementioned difference between the study reported by Shapira and Schexnayder [27] and the current study may be attributed to the different type of cranes used on the examined projects—mobile cranes in the former study as opposed to tower cranes now. Indeed, the difference in crane type represents a distinct difference in equipment planning culture, as observed by Shapira and Glascock [28]. Specifically, equipment planning with mobile cranes is predominantly intuitive and informal to suit the cranes' flexible employment pattern, whereas using tower cranes requires rigorous analysis and therefore involves a greater number of participating functionaries. This increase in the number of parties involved is, however, mostly attributable to the great difference in project size, represented in Table 3 by project cost and duration. (Note particularly the difference in costs: in the 1999 study costs ran in the range of $1–30 M for 31 of the 36 projects surveyed, hence the comparatively low median; costs in the current study were converted from Euros to US Dollars according to currency conversion rates in effect during 2013.)

In an earlier construction planning study, Laufer et al. [26,29] examined, among other things, the degree of involvement of various potential parties in nine functional plans. Their analysis was based on data collected through personal interviews from 18 projects executed by eight leading construction companies in western US. One of the nine functional plans, termed by the researchers "major equipment," was equivalent to equipment planning in the current study. Laufer et al. found that the number of participating parties with considerable involvement (the three upper levels on a six-level scale of degrees of involvement) in major equipment in more than 50% of their sample projects was 2, 1, and 3 in PBP, PCP, and DCP, respectively (mean of 2). Major equipment was only one of nine plans examined in that study and therefore the depth of its investigation was probably lesser than in the current study. Additionally, the analysis technique used by Laufer et al. [26,29] differs slightly from ours. But even when these two variances are taken into account, the difference between the results—2 participating parties compared with 5, on average—is rather telling, and the difference in PCP is even more striking (see Table 4). Here, again, the projects—commercial, public, industrial and R&D facilities—were not what we termed megaprojects in the current study, although they were larger than the 36 projects addressed in the 1999 study (see Table 3).

Table 3. Compared studies.

Study	Number of Projects	Project Cost (Million $)		Project Duration (Month)	
		Range	Median	Range	Median
Current	10	130–650	260	23–48	33
Shapira and Glascock 1996; Shapira and Schexnayder 1999	36	1–200	5.5	3–28	8
Laufer et al. 1993, 1994	18	10–195	58	7–50	23

Table 4. Participating parties.

Study	Mean Number of Considerably Involved Parties				Key Involved Parties [a]			
	PBP	PCP	DCP	Overall	PBP	PCP	DCP	Overall
Current	4.4	6.8	4.2	5.1	HO, PM	PM, PE, HO, GS, EM, SE	GS, PE, PM	PM, GS, PE, HO
Shapira and Schexnayder 1999	2.4	3.5	3.0	3.0	HO, PM	SC, PM, GS	GS, SC, PM	PM, GS, SC
Laufer et al. 1993, 1994	2.0	1.0	3.0	2.0	PM, HO	GS	GS, PM, PE	PM, GS

Notes: PBP: prebid planning; PCP: preconstruction planning; DCP: during-construction planning; PM: project manager; HO: home/company office; PE: project engineer; GS: general superintendent; SC: subcontractors; EM: equipment manager; SE: structural engineer. [a] Parties are listed in descending order of their degree of involvement.

The identity of the key professionals involved in equipment planning at each of the project stages is also of interest. As Table 4 reveals, the key players in PBP are same in all three studies, namely the project manager and home office. A high degree of similarity is seen also in DCP, in which the general superintendent takes the leading role and is joined, other than by the project manager, by the project engineer or subcontractors. In PCP, however, key participating parties in equipment planning for megaprojects include—in addition to the project manager and general superintendent—also the home office, the equipment manager, and the structural engineer. The role of these additional players, as well as several other functionaries, is elaborated on in the next section.

4.2. Uniqueness of Involved Parties

Previous studies showed that the very same "classic" parties—the home office, project manager, general superintendent, project engineer, and often subcontractors—were repeatedly involved in equipment planning for regular sites throughout project life, albeit with changing roles and intensities. The current study, however, brings to the focus various other functionaries as important players in equipment planning for multi-crane sites. This was apparent right from the beginning of the study, when project managers approached in order to schedule site interviews often chose to bring along additional parties. The roles of these other functionaries in equipment planning then became evident from the responses of the interviewees to specific questions.

Overall, in nine of the ten projects studied, at least one functionary other than those listed above was involved to a high or moderate degree in equipment planning in at least one of the three planning stages. At least two such functionaries were highly or moderately involved in at least two of the planning stages in six of the projects, and at least three were involved in all PBP, PCP and DCP stages in five of the projects. Two projects respectively involved, throughout project life, eight and six different participating parties other than the classic ones—the maximum observed in this study. PCP is the planning stage at which the participation of such parties was the highest in seven of the ten investigated projects.

The additional parties with the highest frequency of high or moderate involvement were the company's safety manager and equipment manager, and the crane supplier. The former two were highly or moderately involved in seven and six of the ten projects, respectively (and to a lesser degree in three and two more projects, respectively); the crane supplier was highly or moderately involved in a smaller number of projects—four (and to a lesser degree in two additional projects)—but in three of these four projects that involvement was high in either two or three of the planning stages. The involvement of the crane supplier is, understandably, correlated with the mode of crane procurement: it is expected to be high in projects whose cranes—all or part of them—are rented and to be much lower or non-existent in projects where the cranes are owned by the construction company. In the current study, the cranes were all rented on four projects (see Table 2), of which the crane supplier was highly involved on three. The crane supplier was also involved, albeit to a lesser degree, on the sole project of the ten-project sample in which five of the nine cranes were rented and the others were owned by the contractor. The company's equipment manager plays a similar role, but not as distinctly and with an inverse mode. The equipment manager's involvement is expected to be higher when the contractor uses the company's own cranes and lower when the cranes are rented. Of the six projects in which the equipment manager was highly or moderately involved, four used contractor-owned cranes and one was the project with the partially-owned partially-rented cranes. Only one project in which all (nine) cranes were rented exhibited moderate involvement of the equipment manager (and only in PCP); the involvement of the crane supplier in that project was high and in both PBP and PCP.

Two other parties, associated with crane-related issues, that showed high or moderate degrees of involvement on some of the projects—always in PBP or PCP—were the structural engineer and geotechnical engineer. the structural engineer was commonly the design engineer of the constructed building itself who was consulted on issues such as temporary shoring of slabs in case of an internally-climbing crane or anchoring of an externally-climbing crane to the façade; the geotechnical engineer—also commonly part of the building's design team—was consulted mainly on issues concerning crane foundations.

Perhaps the two most unique parties involved in equipment planning that were identified in the current study are a public relations (PR) functionary and the local authorities. These two parties, who represent the interface between the site and its surroundings, were kept in the picture of equipment planning on all of the examined projects, although for the most part they did not actively participate in the planning process itself. However, in some of the projects, the active involvement of the authorities and PR was recognized by the interviewees, and was even rated as high or moderate on three and two of the projects, respectively (and as low on two of the remaining projects), always in PCP and/or DCP. This rating was acquired only after the interviewees understood the involvement of these two parties should be rated only if they were actually consulted as part of the selection process and not if they were merely updated later and were expected to deal with the consequences (PR) or if various regulations were simply taken into consideration (authorities). The PR functionary (on one project the job title was even more specific: PR-logistics) typically addressed the concerns of neighboring residents and near-by facilities (e.g., hotels, hospitals) regarding traffic, noise, and nighttime lighting. Examples of issues on which the authorities were brought into the equipment planning process are the need for temporary road closing during construction, off-limit zones for oversailing of crane jibs outside the site boundaries (e.g., above a busy train station), and securing helicopter routes of to and from the roof of an adjacent hospital.

Finally, two additional parties, external to the site or the construction company, whose involvement emerged from the current study, should be mentioned as unique participants in the equipment planning process for mega building projects. The first of these is the owner, who although not new as a party participating in construction planning at large, is commonly not involved in equipment planning per se. In the current study, however, owners were found to be involved in five projects to various degrees (in PBP and/or PCP), and in one of these projects the owner was even highly involved (in PBP, and moderately in PCP). The owner's involvement was found to be highly correlated to the project's delivery method in which the owner joined forces with the construction company to execute the project as a joint venture. In one of these projects, for example, it was the owner's construction planner, rather than the contractor's project manager, who presented the research team with the actual layout of the nine cranes and the rationale for crane selection and location.

The second external party worth mentioning here is the construction company's management, which is normally not expected to take part in equipment planning for common-size projects, particularly not in companies the size of those that built the projects examined here. Yet company management was identified as a highly involved party in two projects (in PCP), which is another demonstration of the uniqueness of multi-crane sites in terms of equipment planning.

4.3. Multiplicity of Plan Formats

Laufer et al. [26,29] recognized that the mere issuing of a documented plan and, even more so, the multiplicity and variety of formats used for plans, is an indication of both the rigor of planning and the progressiveness of the construction company's planning culture. In light of this, and given both the nature of the examined projects and the reputation of the contractors executing them, similar findings were expected in the current study.

The most noteworthy of the findings, summarized in Table 5, is that, on average, eight different format types were used to document the outcome of equipment planning on each project. The respective number found by Laufer et al. [26] was 1.2 (mean number of the results reported by Laufer et al. separately for PBP and PCP; they did not study the use of format types in DCP). This striking difference may be explained in part by slight differences between the two study methods, e.g., the current study used 13 formats whereas Laufer et al. used 11 formats in their study. Furthermore, since Laufer et al. investigated nine functional plans and did not particularly focus on equipment planning, four of these 11 formats were a priori irrelevant to equipment planning (e.g., organizational structure, work breakdown structure). On the other hand, the one format type that Laufer et al. called "drawings" was addressed here as three different types (layout, elevations, and detailing), given the requirements of equipment planning. And yet, the over-500% increase in the mean number of format types stems primarily from the size and complexity of the sample projects in the current study; to the planning rigor that these size and complexity necessitate; and to the centrality, in general, of equipment planning in construction planning for multi-crane building projects.

The multiplicity of format types was most noticeable in PCP, while in DCP the rate of multiple format utilization was the lowest (rightmost column in Table 5). Drawings of layouts and elevations were the most frequently used formats in PCP, followed closely by meeting protocols, calculations, and Gantt charts. Overall, these five formats, led by meeting protocols (which was the only format used extensively in DCP), were also those most used in all projects (bottom line in Table 5). When analyzing the extent of format use in terms of format families, drawings of various types emerge, clearly, as the most frequently used medium. This result is quite understandable given the centrality of cranes in the site's production array, on the one hand, and the geometrical complexity associated with their planning, on the other. This centrality can also explain the relatively low use of various types of drawings (and of most other format types, for that matter) in DCP. Indeed, when dealing with tower cranes, equipment planning cannot leave much room for flexibility during construction; the employment pattern and working mode of the cranes [28] make it imperative to essentially complete planning before construction commences, particularly on sites with multiple cranes.

Table 5. Formats of plans.

	Format	Planning Stage			[Mean]
		PBP *	PCP	DCP	
Number of projects per format type	Notes taken after phone call	5	7	5	5.7
	Meeting minutes	10	9	10	9.7
	Checklist	5	7	5	5.7
	Table	6	6	5	5.7
	Calculation	10	9	3	7.3
	Standard form	6	5	7	6.0
	Graph	6	5	2	4.3
	Sketch	6	6	4	5.3
	Flowchart	2	3	3	2.7
	Gantt chart	9	9	6	8.0
	Drawing: layout	9	10	5	8.0
	Drawing: elevation	9	10	5	8.0
	Drawing: detailing	0	8	4	4.0
	All format types	83	94	64	80.3
Mean number of format types per project		8.3	9.4	6.4	8.0

Notes: PBP: prebid planning; PCP: preconstruction planning; DCP: during-construction planning. * Numbers normalized for ten projects (original entries were for eight projects, as two projects did not have PBP due to their delivery method).

It is noteworthy that, while in the current study the variety of format types exhibited in PCP is 13% higher than in PBP, Laufer et al. [26] found the opposite: variety in PBP was 4% higher than in PCP for major equipment (mean number of formats was 1.20 and 1.15, respectively). Thus, the dominance of PCP in the current study, identified already in terms of the multiplicity of involved parties, is further substantiated by the multiplicity of plan formats exhibited.

Finally, it should be noted that, although the aforementioned Laufer et al. studies took place some two decades ago, plan formats fundamentally have not changed since then; the interviewees in the current study did not add formats to the list presented to them although they were encouraged to do so. Naturally, what did change are the production means of plans, which are nowadays produced digitally.

4.4. Company Reputation and Visibility

The importance accorded by the construction company to its reputation and visibility as factors considered in the course of equipment planning was one of the unique characteristics of multi-crane sites identified in the current study. The most noticeable and immediate (albeit initially only alleged) indication was the uniform appearance of the tower cranes on the site. When contractors use their own cranes, they have better control over visual maintenance (e.g., periodical paintwork) and over the types used on any given project, compared with rented cranes. But even then, the cranes might not always be in best of shape and exhibit uniform appearance, as this has much to do with company tradition and culture. When cranes are rented, control over visual maintenance is obviously low to begin with. Yet, on all the ten sites investigated, including the five with exclusively or partly rented cranes, the sight of the crane forest was unique in terms of uniformity of crane color and visual care (and, on six of the sites, also in terms of crane manufacturers). The following examples demonstrate how the project—and not the manufacturer or rental company, nor the construction company—was the governing factor in determining crane color (see Table 2): (1) the nine cranes on project 2-DE, all rented, were Wolffkran cranes painted red; (2) the five cranes on project 9-DE, all company-owned, were Liebherr cranes painted green; (3) the nine cranes on project 4-DE, five rented (four Liebherr and one Wolffkran) and four company-owned (three Liebherr and one Potain), were all painted yellow; and (4) of the two projects constructed by Züblin, the five rented Wolffkran cranes on project 5-DE were painted red, whereas the 12 company-owned cranes on project 10-DE—nine Wolffkran and three Liebherr—were all painted yellow.

This initial visual impression was substantiated later when interviewees were questioned about the role that visibility and reputation played in equipment planning. In the open discussion, nearly all of them admitted to increased sensitivity to "appearance" in such large-scale projects located in the midst of the urban scene, particularly if the project was "at the focus of the media (press, TV)," as one project manager put it. With specific regard to company reputation as a factor influencing crane selection, the influence on one project was deemed to be of a supportive nature, while on one other project it was even seen as having a dictating nature. Finally, the participation of an assigned PR functionary in the equipment planning team also attests to the importance attributed by the construction company to visibility and reputation, far beyond what is common in smaller projects.

4.5. Public Sensitivity

To check the sensitivity of the various construction companies to the needs of the public near the mega sites during construction and its influence on equipment planning, the interviewees were asked to address several actions potentially taken by the project's management. This was the only part of the interview in which respondents were encouraged to refer not only to their current project but also to their cumulative experience managing large-scale building projects. The list of potential actions relevant to public sensitivity included: (1) sharing information with the public; (2) special access provisions; (3) reduced noise levels; (4) keeping the vicinity of the site clean; and (5) special provisions for awaiting trucks. This list was compiled from the literature [31] and following the preliminary site visits and interviews conducted as part of the current study.

On all but two projects, sharing information with the public in the immediate vicinity of the site (mainly residents of nearby buildings) and accommodating their needs to the greatest extent possible were considered a crucial element of project management in general and of its equipment planning component in particular. This action took various forms, such as weekly or biweekly newsletters distributed to the neighbors, periodical (usually monthly) meetings with neighborhood representatives or any interested neighbors, visits to the site, and advance notification regarding certain specific operations (mainly large concrete pours, arrival of oversize vehicles, and exceptionally late night work hours). Issues of mutual concern related to equipment and logistics were, for example, partial blocking of access lanes and parking spots by trucks arriving at the site, road cleaning, occasional oversailing of crane jibs outside the site's boundaries and above public areas, and noise from machines operating at late hours. These issues were even more pronounced in the investigated sites given their size and work intensity, combined—in most cases—with central locations in busy urban settings. The two projects for which similar actions were not reported were surrounded by relatively large open spaces such that they did not interfere with daily life of the neighbors, despite being located in the heart of the city. The majority of respondents who attested to unique actions that stemmed from the large scale and location of their current projects had experienced similar situations in similar projects they were involved with in the past.

Given the nature of the above-listed issues and actions, most equipment and logistics planning attributable to sensitivity to the needs of the public were conducted in DCP. There were, however, examples during PCP as well. In one project, new power trowels were purchased by the contractor only because their engines were known to produce lower noise levels than the equipment the company already owned. On that particular project, and on one other project, the contractor purchased designated cleaning machines that washed the streets immediately after they were soiled by trucks (during ground works) and later by concrete mixers. Generally, electrical equipment was favored, as much as possible, over petrol or diesel powered equipment. One obvious, fundamental feature of the electrical tower crane—its quiet operation—constituted a great advantage on sites employing multiple such machines in the heart of the city near hotels, hospitals, and schools, or in close proximity to residential areas. This attention paid by the construction company to the needs of the public around the mega site partially contradicts findings reported by Close and Loosemore [32], whose study did not focus on mega projects. Based mainly on responses to questionnaires received from 150 construction professionals in the UK, Australia and New Zealand, Close and Loosemore found that community concerns were perceived to be the responsibility of town planners before work starts; once work started, interaction with the community was viewed as a nuisance and community consultation was considered a burdensome, costly, and time-consuming exercise. Spillane et al. [33] report on typical issues raised that concern the interface between the urban construction site and the community and the strategies enacted to addresses these issues. However, their study did not investigate the actual attitude of the construction professionals they interviewed toward community consultations.

4.6. Crane Overlapping

Given the circular shape of crane work envelopes, overlapping is unavoidable if the entire building footprint and most of the staging areas are to be covered by the cranes. Crane work in shared zones created by the envelopes of adjacent cranes overlapping each other requires more caution and is therefore slower; requires real-time, continuous coordination between operators; and is often interrupted to give way to the other, overlapping crane. Productivity is therefore affected and safety becomes a matter of greater concern. While this is true on any site employing at least two overlapping cranes, it is particularly an issue on multi-crane sites.

The investigation of crane layouts in the current study was conducted both through visual examination of plans supplied by the project managers and the questioning of the interviewees. The main findings are summarized as follows:

- A significant proportion of the site's area—including almost the entire footprint of the building—is covered by overlapping work envelopes. This is due to the common two-dimensional crane array made necessary by the building's footprint geometries on most megaprojects (as opposed to the less-common linear crane array on projects whose building footprint geometry is long and narrow).
- There is a substantial number of locations where three and even four cranes overlap, creating a particular challenge to safe work. For example, the layout presented in Figure 1 reveals three locations in which four cranes overlap and 16 locations with three intersecting cranes; hazardous contact between two cranes (typically between the hoisting cable or hook block of the higher crane and the jib of the lower crane) might occur even in the tiniest of shared work zones. (Note: in the less-common case of a linear array, the number of overlapping cranes at each intersection location would be only two. A similar, and even less common case, is that of a circular crane array in stadium construction.)
- Whereas the work envelope of each individual crane on a regular site is commonly characterized by two, three, or—at the most—four different zones (one shared and one non-shared in the case of two overlapping cranes; two shared and one non-shared in the case of three or more cranes overlapping in a linear layout; one shared by three cranes, two shared by two cranes, and one non-shared zone in the case of three cranes overlapping each other), crane envelopes on multi-crane sites are characterized by multiple different zones. For example, the work envelope of crane K10 in Figure 1 contains as many as 12 different zones; the envelope of K5 contains 15 zones, and those of K1 and K8 contain "only" 9 zones each. If the jib length of K6, currently at 35 m, were extended by merely 5 m, K1 would see 10 zones, K10 14 zones, and K5 as many as 18 zones. Thus, each of the 12 crane envelopes in the layout shown in Figure 1 contains an average of 9 different work zones. The amount of coordination and communication needed between operators is immensely greater than on regular sites, and so the most competent and skilled crane operators available are required. (Although the above-listed analysis literally counts most zones more than once when considering the entire site, it actually reflects realistically the work arena

of any single crane operator and his/her ensuing handling of safety and productivity concerns, which are the issues here.)

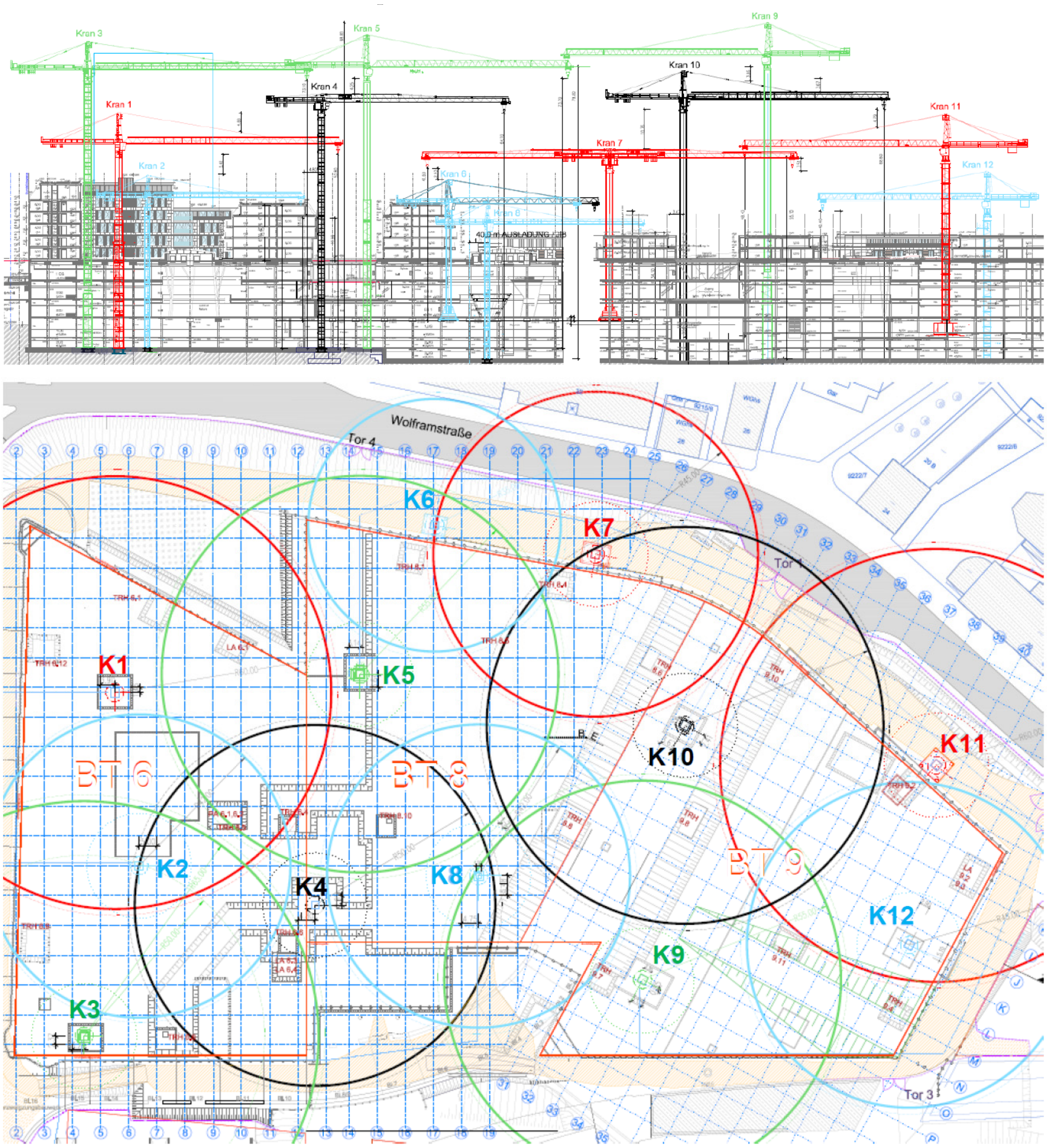

Figure 1. Multi-crane site (12 tower cranes): top–elevation; bottom–plan.

- In the two-dimensional crane array common on multi-crane sites, some of the cranes are typically located in the depth of the site (see, for example, cranes K5, K8, and K10 in Figure 1). Whereas the setup of these cranes before construction starts is a standard operation, not much different from that of the peripheral cranes in the array, their dismantling after construction ends may pose a difficult problem. This is true even if the large dismantling mobile crane has access from all sides of the completed project; if access from some sides is limited or impossible, not only is the challenge even greater (i.e., the dismantling crane must have a longer reach and higher lifting capacity), but it concerns more cranes on the site. Indeed, crane dismantling was a problem on six of the investigated projects in the current study, which was solved by taking crane dismantling into consideration already in the crane selection stage. Jib lengths, lifting capacities, and crane locations were determined such that some of the tower cranes could dismantle adjacent cranes before being themselves dismantled by a mobile crane. On some sites, this was even planned as a three-phase operation: tower crane A was to be dismantled by tower crane B, which was then to be dismantled by tower crane C before a mobile crane dismantles the latter. On one of the projects, four of the nine cranes were to dismantle the other five cranes before being themselves dismantled.

- Materials delivered to the site are sometimes needed in parts of the building where the crane is too busy to unload the truck or has a load capacity that is lower than that required to handle the lift. In such cases, another crane is assigned to the task and crane overlapping is used to transport the materials to their final destination (i.e., "double handling"). Similarly, crane overlapping is used when access restrictions prevent trucks from unloading materials where they are needed.
- In the electronic age, crane operators have various advanced technology systems at their disposal to assist work in shared zones, manage blind lifts, avoid obstacles, and define forbidden zones for slewing and/or trolleying [34]. To help cope with multi-crane zones, anti-collision systems were used on four of the ten projects in the current study: the three British projects and the single French project. No such systems were used on any of the German projects (but electronic limitation of forbidden zones was implemented in three of them, in addition to the aforementioned four projects). While anticollision systems are mandatory in France and strongly recommended (though not mandatory) and widely used in the UK, German contractors have been slower to adopt them [35–38]. The fact that anticollision systems are not popular among German tower crane operators was confirmed also by the interviewees themselves, who represent leading construction companies and build on their cumulative experience with multi-crane sites.

4.7. Miscellaneous

The current study identified several other unique characteristics, all of which relate distinctly to logistics planning and management; since they are only peripheral to equipment planning, they are mentioned here only briefly. Common to most of the investigated projects were:

1. Outsourced logistics planning: acquiring the services of an external designated firm to plan the logistics array for the project (on six of the projects).
2. Outsourced logistics management: subcontracting the daily management of materials ordering, delivery to the project, and supply to required locations on site (on eight of the projects).
3. Just-in-time supply: directly from the hauling trucks to the building due to lack of storage space (on nine of the projects).

Offsite interim storage is also worth mentioning, although it was found on only two of the investigated projects. Use of such storage results from a lack of storage space for the enormous amount of materials needed combined with frequent difficulties in timely deliveries to the site due to congested traffic, as well as the need to secure scheduled supplies. A designated site, typically located near the construction site, serves for interim storage and regulation of materials delivery to the site.

5. Conclusions

With respect to the four questions posed at the beginning of the paper, this study found that (1) other than the mere effect of magnitude, multi-crane sites are characterized by unique features that clearly distinguish them from smaller sites; (2) equipment planning for multi-crane building projects differs significantly from that conducted for regular projects; (3) the site-surroundings interface affects equipment and logistics planning for multi-crane projects to a greater extent than for smaller projects; and (4) the awareness of reputation plays a role in crane selection.

These insights were acquired through in-depth case studies of ten multi-crane building projects augmented by long discussions with four leading experts. The group of investigated projects was homogenous in terms of projects' singular nature (each was a *single* building constructed by a *single* general contractor as a *single* project), distinct horizontal dimension, and busy urban location. In all other respects, it was diverse (e.g., in terms of uses, contractors, and city of location) to allow for as many unique aspects of such projects to surface.

Specifically, the main findings and their implications are as follows:

- *Planning parties*: The number of different functional parties exhibiting considerable involvement in equipment planning in the current study, across all planning stages and particularly in preconstruction planning, was about twice as high as the respective numbers identified in previous studies of regular, non-multi-crane sites. Distinct equipment planning parties for multi-crane sites were the crane supplier, the construction company's safety manager and equipment manager, the structural and geotechnical engineers, a PR functionary, and representatives of the local authorities. Given the magnitude of the projects at stake, both the owner and the construction company's top management were also involved in equipment planning. Thus, equipment planning for multi-crane projects becomes a major managerial undertaking that necessitates preparations on behalf of the construction company for a thorough, multiphase decision-making process, including the allocation of appropriate human and engineering resources and the definition of the information to be introduced into the process by each functionary at each phase.
- *Plan formats*: the average number of different format types used to document the outcome of equipment planning on the studied projects was about six times the respective number found in previous studies of regular projects. The wealth of different plan formats included meeting minutes, calculations, Gantt charts, and drawings of layouts and elevations. These were used on nine of the ten investigated sites or on all of them during both prebid and preconstruction planning. The extensive use of Gantt charts is particularly noticeable and reflects the need to plan and monitor the varying service durations, as well as staggered setup and dismantling timings, of a great number of cranes throughout a long construction period.
- *Reputation and visibility*: companies are aware of the potential contribution to their reputation of the appearance of a crane forest in the midst of busy urban locations viewed daily, both directly by near and far onlookers and indirectly by many more through the media. To maximize the effect, companies go to the trouble of ensuring a unique and neat appearance of same-color cranes, even when using cranes of different manufacturers on the same site and when using rental cranes.
- *Public sensitivity*: the investigated projects made a strong impact during construction, both on their physical environment and on the daily routine of people living, working, or otherwise present in the neighborhood. This was due to the large footprint of the sites, their central location, long construction time, and constant traffic of equipment and materials to/from the sites. Various actions were taken by project managements to share information with the neighboring residents and businesses and to alleviate the hardships of living and working near a busy construction site as much as possible. Particular steps were taken in terms of types of equipment employed on site, work schedule of various construction activities, and logistics that affected the site's vicinity.
- *Crane layouts*: from any angle we look at it, a site employing nine cranes, for example, cannot be treated as if it was simply three sites with three cranes each. The multiplicity of cranes working in multiple shared zones poses managerial and safety challenges alike. It is not exceptional to have 10 to 15 different work zones within one crane envelope, a situation that entails the employment of the most competent, experienced, and highly trained operators. The cautious work affects production rates and therefore it should be taken into consideration when planning daily and weekly work schedules. Interestingly, no anti-collision systems were used on any of the six German projects studied here; in a culture that places the utmost importance on safety, there is apparent reliance on the skills and experience of all those involved in lifting (operators, lift directors, slingers and signalers).

- *Logistics*: given the magnitude and complexity of the projects studied here, planning and subsequently ongoing management of logistics were mostly outsourced and scarcity of storage space entailed the use of just-in-time deliveries of supplies.

The planning and execution of today's construction projects are constrained by shortage of labor and its escalating costs, pressures to accelerate construction schedules, and the need to increase production rates. Increased industrialization potentially provides solutions to these constraints, and thus more and more projects nowadays tend to use a greater number of cranes than they would have in the past. However, the resulting increase in the number of multi-crane building sites has not yet been adequately accompanied by due research, and proper understanding of the unique nature of such sites with regard to equipment planning has yet to be attained. This study aspired to help close this knowledge gap.

Limitations and Future Research

This paper is based on ten case studies. Since the aim was to identify and analyze, for the first time, the unique equipment planning characteristics of multi-crane projects, the suitable methodology appeared to be one of depth rather than breadth. Long face-to-face interviews of senior experienced professionals, preceded by a preliminary study of the said projects and followed by an investigation of specific complementary material provided subsequently by the sites, helped expose findings that would not have been obtainable using a research method such as the distribution of questionnaires to a larger project population. Having pinpointed the main unique characteristics of equipment planning for multi-crane sites, it is now possible to expand the current study with a similar—albeit a more focused—one, in which a larger population of projects will be used to accord statistical significance to the observations found here.

This research was conducted exclusively in Europe; more specifically, most of the projects (six out of ten) were in Germany. Construction practices may be different in various world regions and markets. It would be interesting to reveal how some of the findings and conclusions of the current study might change in other construction cultures.

By exposing and analyzing the unique characteristics of equipment planning on multi-crane projects, the current paper underlines the importance of these functions in the overall construction planning of such projects and implicitly suggests that their potential contribution to the success of such projects is greater than in regular projects. A future study will attempt to substantiate this hypothesis with regard to both meeting the three classic project goals—budget, schedule, and quality—and satisfying safety and sustainability requirements.

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References

1. Szyliowicz, J.S.; Goetz, A.R. Getting realistic about megaproject planning: The case of the new Denver International Airport. *Policy Sci.* **1995**, *28*, 347–367. [CrossRef]
2. Zeitoun, A.A. Managing projects across multi–national cultures, a unique experience. In *Proceedings of the 29th Annual Project Management Institute 1998 Seminars and Symposium*; PMI: Newton Square, PA, USA, 1998.
3. Brockmann, C. Development of construction methods for international mega-projects. In Proceedings of the 1st FIB Congress, Osaka, Japan, 14–18 October 2002.
4. Kim, S.-G. Risk performance indexes and measurement systems for mega construction projects. *J. Civ. Eng. Manag.* **2010**, *16*, 586–594. [CrossRef]

5. Lundrigan, C.P.; Gill, N.A. *Megaprojects: A Hybrid Meta-Organisation*; Working Paper 14/1; Centre for Infrastructure Development, University of Manchester: Manchester, UK, 2013.
6. Fiori, C.; Kovaka, M. Defining megaprojects: Learning from construction at the edge of experience. In Proceedings of the Construction Research Congress, San Diego, CA, USA, 5–7 April 2005; ASCE: Reston, VA, USA, 2005.
7. Oliomogbe, G.O.; Smith, N.J. Value in megaprojects. *Organ. Technol. Manag. Constr.* **2013**, *4*, 617–624.
8. Hu, Y.; Chan, A.P.C.; Le, Y.; Jin, R-.Z. From construction megaproject management to complex project management: A bibliographic analysis. *J. Manag. Eng.* **2015**, *31*. [CrossRef]
9. Van Marrewijk, A.H.; Smits, K. Understanding cultural practices of governing in the Panama Canal Extension megaproject. *Int. J. Proj. Manag.* **2016**, *34*, 533–544. [CrossRef]
10. Flyvbjerg, B.; Bruzelius, N.; Rothengatter, W. *Megaprojects and Risk: An Anatomy of Ambition*; Cambridge University Press: Cambridge, UK, 2003.
11. Fainstein, S.S. Mega-projects in New York, London and Amsterdam. *Int. J. Urban Reg. Res.* **2008**, *32*, 768–785. [CrossRef]
12. Sanderson, J. Risk, uncertainty and governance in mega projects: A critical discussion of alternative explanations. *Int. J. Proj. Manag.* **2012**, *30*, 432–443. [CrossRef]
13. Barakat, T.A.H. A Hybrid Model of Communication and Information Management in Mega Construction Projects in Dubai Using a New Critical Success Factor Approach. Ph.D. Thesis, Loughborough University, Loughborough, UK, 2009.
14. Frick, K.T. The cost of the technological sublime: Daring ingenuity and the new San Francisco-Oakland Bay Bridge. In *Decision-Making on Mega-Projects: Cost-Benefit Analysis, Planning and Innovation*; Preimus, H., Flyvbjerg, B., van Wee, B., Eds.; Edward Elgar Publishing: Cheltenham, UK, 2008.
15. Sykes, A. Megaprojects: Grand schemes need oversight, ample funding. *Forum Appl. Res. Public Policy* **1998**, *13*, 6–47.
16. Zhang, P.; Harris, F.C.; Olomolaiye, P.O.; Holt, G.D. Location optimization for a group of tower cranes. *J. Constr. Eng. Manag.* **1999**, *125*, 115–122. [CrossRef]
17. Tam, C.M.; Tong, T.K.L.; Chan, W.K.W. Genetic algorithm for optimizing supply locations around tower crane. *J. Constr. Eng. Manag.* **2001**, *127*, 315–321. [CrossRef]
18. Alkriz, K.; Mangin, J.-C. A new model for optimizing the location of cranes and construction facilities using genetic algorithms. In Proceedings of the 21st Annual ARCOM Conference, London, UK, 7–9 September 2005; Khosrowshahi, F., Ed.; University of London: London, UK, 2005; Volume 2, pp. 981–991.
19. Kang, S.C.; Miranda, E. Computational methods for coordinating multiple construction cranes. *J. Comput. Civ. Eng.* **2008**, *22*, 252–263. [CrossRef]
20. Irizarry, J.; Karan, E.P. Optimizing location of tower cranes on construction sites through GIS and BIM integration. *J. Inf. Technol. Constr.* **2012**, *17*, 351–366.
21. Lien, L.-C.; Cheng, M.-Y. Particle bee algorithm for tower crane layout with material quantity supply and demand optimization. *Autom. Constr.* **2014**, *45*, 25–32. [CrossRef]
22. Zavichi, A.; Madani, K.; Xanthopoulos, P.; Oloufa, A.A. Enhanced crane operations in construction using service request optimization. *Autom. Constr.* **2014**, *47*, 69–77. [CrossRef]
23. Wang, J.; Liu, J.; Shou, W.; Wang, X.; Hou, L. Integrating building information modelling and firefly algorithm to optimize tower crane layout. In Proceedings of the 31st International Association for Automation and Robotics in Construction (ISARC 2014), Sydney, Australia, 9–11 July 2014.
24. Harzing, A.-W. Response styles in cross-national survey research. *Int. J. Cross Cult. Manag.* **2006**, *6*, 243–266. [CrossRef]
25. Shapira, A.; Laufer, A. Evolution of involvement and effort in construction planning throughout project life. *Int. J. Proj. Manag.* **1993**, *11*, 155–164. [CrossRef]
26. Laufer, A.; Shapira, A.; Cohenca-Zall, D.; Howell, G.A. Prebid and preconstruction planning process. *J. Constr. Eng. Manag.* **1993**, *119*, 426–444. [CrossRef]
27. Shapira, A.; Schexnayder, C.J. Selection of mobile cranes for building construction projects. *Constr. Manag. Econ.* **1999**, *17*, 519–527. [CrossRef]
28. Shapira, A.; Glascock, J. Culture of using mobile cranes for building construction. *J. Constr. Eng. Manag.* **1996**, *122*, 298–307. [CrossRef]

29. Laufer, A.; Tucker, R.L.; Shapira, A.; Shenhar, A. The multiplicity concept in construction project planning. *Constr. Manag. Econ.* **1994**, *12*, 53–66. [CrossRef]
30. Cohenca-Zall, D.; Laufer, A.; Shapira, A.; Howell, G.A. Process of planning during construction. *J. Constr. Eng. Manag.* **1994**, *120*, 561–578. [CrossRef]
31. Glass, J.; Simmonds, M. "Considerate construction": Case studies of current practice. *Eng. Constr. Archit. Manag.* **2007**, *14*, 131–149. [CrossRef]
32. Close, R.; Loosemore, M. Breaking down the site hoardings: Attitudes and approaches to community consultation during construction. *Constr. Manag. Econ.* **2014**, *32*, 816–828. [CrossRef]
33. Spillane, J.P.; Flood, M.; Oyedele, L.O.; von Meding, J.K.; Konanahalli, A. Urban high-density construction sites and their surrounding community: Issues encountered and strategies adopted by contractors. In Proceedings of the 29th Annual Association of Researchers in Construction Management Conference (ARCOM 2013), Reading, UK, 2–4 September 2013.
34. Shapira, A.; Lucko, G.; Schexnayder, C.J. Cranes for building construction projects. *J. Constr. Eng. Manag.* **2007**, *133*, 690–700. [CrossRef]
35. Voyatzis, A. Anti-collision technology: Dynamic avoidance. *Cranes Today* **2007**, *334*, 31–35.
36. British Standards. *Code of Practice for Safe Use of Cranes*; Part 5: Tower Cranes, BS 7121; BSI: London, UK, 2006.
37. North, W. Anti-collision systems: A clash of cultures. *Cranes Today* **2007**, *388*, 25–29.
38. Overdahl, S. ConstructionWeekOnline.Com. Anti-Clash Tech on the Burj Plot. 2013. Available online: www.constructionweekonline.com/article-21304-anti-clash-tech-on-the-burjplot/1/ (accessed on 14 July 2017).