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Initial Analysis, Planning and Calculation of Vertical Transportation in Construction

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Abstract

The tower crane is one of the major (key) equipment used in high-rise buildings construction. The main challenge encountered in the construction of high-rise buildings is the transportation of construction materials vertically and horizontally to the required or specific areas of the project. To tackle this challenge various equipment such as tower cranes, mobile cranes, hoists, etc., are used and out of all these equipment tower crane plays a vital role in the logistics of construction materials in the construction projects. Investors and General contractors very often use technical and commercial offers from the crane renting companies to make decisions concerning the number of cranes and period of engagement in the project. There is always a commercial and time risk involved to the Clients in the selection of cranes based on the offers from crane companies, as mostly these crane companies would try and sell what they have in their hand opposed to the most time and cost efficient options for the project. The main reason for that risky approach is a lack of standardized methodologies for the tower crane productivity calculation and decision-making on the selection of models for different proposed solutions by specialists. Identifying optimal number, location and duration of operations on the site are the major factors that can reduce the possibilities of the project outrun over the budgeted time and cost by increasing the productivity and lessen the time of construction. Often tower cranes operate with overlapping works zones, and under time, cost and labor constraints. Therefore, proper planning to be considered, while choosing a tower crane, based on different production parameters such as optimal space per worker, concrete production per crane or worker, lifting time, crane booms overlapping, health and safety measures, and crane operators well-being during the crane operation with maximum visibility to the work areas. In this paper, the methodologies for the number of crane calculation and their optimal positioning in three different construction phases are discussed - underground structures, above ground structure, façade, MEP and finishes work. CPM planning techniques (Primavera P6 software) is used for the proposed model, considering leveling and optimizing of crane usage. An actual case example is provided to demonstrate the planning model for the selection and positioning of tower cranes.

Keywords: construction, optimization, planning, tower crane

1. Introduction

A typical high-rise building construction involves lifting materials of different load size, type and weight, within the determined time with logistics, commercial, health & safety, administrative, programme and other constraints. For instance, let's consider concreting works, which are always in the critical path of high-rise construction projects, to which tower cranes are the most key logistic equipment which defines the programme certainty of these works. Therefore, tower crane needs to be planned appropriately. At present, planning for tower crane operations is mostly performed intuitively and based on experience (Hasan S. et al., 2010).

For any construction project, one of the most important documents are the general construction and logistics plans. General construction plan identifies number of cranes with their position. In authors experience, any delays during the preconstruction period (design, planning approvals, procurement) will be cascaded to the construction period and the project will require a mitigation strategy of all these delays within the construction period. In that case, the best option to reduce or mitigate delays within construction period is by increasing or optimizing number and position of cranes, along with the corrective measure and increasing of required resources (labors, material, other equipment etc.) will increase the production thus reducing the time and delay. In this paper author has analysed a case study from one of the large commercial project with possible suggestions for the improvement and optimization of tower cranes.

2. Methodology

The methodology outlined below was employed to determine necessary tower cranes and their optional location and time for a large commercial construction project. In practice, a tower crane is selected based on the maximum load needs to be lifted, size of the load, site layout, and the reach or capacity (Hasan S. et al, 2010).

Site organization with optimum resources to maximize production is the best way to reduce construction cost. Efficiency of concrete works mostly depend on:

- number, types and position of tower cranes;
- number, specialties of productive workers on site;
- quantity and type of formwork;
- availability of materials and supply 'just in time'.

It is tough to calculate maximum production per worker, because of technological sequences, idle time, weather conditions, skills and physical condition of workers etc. (Hasan et al., 2010) calculated, based on production control, following data presented in the table 1:

process name	available time (min)	cycle time (min)	active (min)	idle (min)	% of utilization
inspection	480	13	429	51	89,38%
crane 1	480	15	255	225	53,13%
crane 2	480	15	240	240	50,00%
installation L1	480	20	340	140	70,83%
installation L2	480	20	320	160	66,67%

Table 1: Calculation of percentage of crane utilization (Hasan et al., 2010)

Based on percentage of utilization, standard construction method analysis and statistical data from three construction sites in Russia during different weather conditions, above results were calculated. It is found that maximum percentage of utilization per crane is only 53,13%. The above simple analysis was based on statistical data of monthly concrete poured (m^3) and number of skilled and unskilled labors assigned to concrete works (reinforcement, formworks and concreting works).

In general, tower crane utilization in construction job sites is estimated to be 50% to 80% (Hasan et al, 2013; Gillis & Telyas, 2013; Kay, 2001, Rosenfeld & Shapira, 1998). Reducing the crane lifting cycle or maximum utilization of tower crane not only increase the crane productivity but also helps in reduction of total project duration

The tower crane during its operation is the most key equipment in the logistics of the critical path activities. Saving in crane operations will have its impact on two major operational factors. First, saving in crane operation will shorten crane cycle time. Second, higher labor productivity is expected due to shortening of the crane operation.

Saving related to the crane operation cost can be divided into four categories:

1. Annual ownership cost: this is a cost of buying a crane throughout its useful life span;
2. Operation cost: included fuel, maintenance, license fees, and insurance;
3. Operator cost: this is salary of the crane operator;
4. Labor cost: cost of the laborer working directly with the crane.

Below, in the table 3, is presented crane operational time on site. Basically, due to the fact that tower cranes stay longer in the project and as their rental rates and mobilizing costs are high. Therefore it is not economical to rent a tower crane for the projects with longer project duration (Rosenfeld & Shapira, 1998; Sullivan et al., 2009).

For the tower cranes production calculation, it was used average production rates from author previous experience, presented in table 2:

- Optimal number of workers per crane during concrete works ≈ 70 workers;
- Winter productivity per worker ≈ 16 m^3/month (Russia);
- Summer productivity per worker ≈ 23 m^3/month (Russia);

From the previously defined data, average production per crane are:

- Production per crane underground (substructure) – 1200 m^3/crane/month;
- Production per crane above ground (superstructure) – 1500-1700 m^3/crane/month.

	jul	aug	sept	oct	nov	dec
Construction site 1 (commercial 185,000 m^3 of concrete)	8450	8920	9650	9790	6140	5920
	375	395	425	465	375	360
Construction site 2 (commercial 210,000 m^3 of concrete)	9230	9610	8420	8890	7290	7140
	390	400	385	395	440	420
Construction site 3 (commercial 320,000 m^3 of concrete)	12610	14100	14340	12220	11600	10650
	555	610	615	580	690	690

Table 2: Concrete production and number of workers on site

A concrete pouring plan is very essential to be defined and it has to be a part of project logistics plan, general construction plan and concrete works method statement. It can be prepared based on concrete quantities from schematic design which will form the basis for initial level 2 time programme. Concrete foundations and frame are always on critical path, and which are subjected to many constraints such as logistics, availability of concrete plants, traffic, pumps, tower cranes, etc. Tower cranes are primarily are used for the logistics of reinforcement, formwork, brickworks, concrete columns and concrete pouring, and for lifting other materials. In this paper two optimization steps are analyzed - determination of minimal number of tower cranes and optimizing location of tower cranes in order to minimize potential conflicts between tower cranes and other facilities. Each crane has his load chart that specifies lifting capacity. The maximum capacity is always obtained by the shortest crane's operating radius. (Irrizary and Karun, 2012).

For the proper planning of crane utilization, it is very important to define various phases of construction. Usually, underground and above ground construction are different from the point of view of tower cranes usage. In that case, the best option to reduce or mitigate delays within construction period is by increasing or optimizing number and position of cranes, along with the corrective measure and increasing of required resources (labors, material, other equipment etc.) will increase the production thus reducing the time and delay.

A proper general construction plan should define the optimal position of the tower cranes. According to (Tam et al., 2001) and (Zhang et al., 1999) in order to lift load at supply point (S) with the weight w, tower crane should be placed within a circle centered at S and with lifting radius R, where R is the minimum of the tower crane's jib length (Cr) and operating radius (r) obtained from load chart. In the proposed model, it is possible to consider more than one demand point for each supply points. In reality, there may be more than one feasible area within a construction site. A tower crane can handle two tasks, if it is located within the area of intersection between than (fig 1).

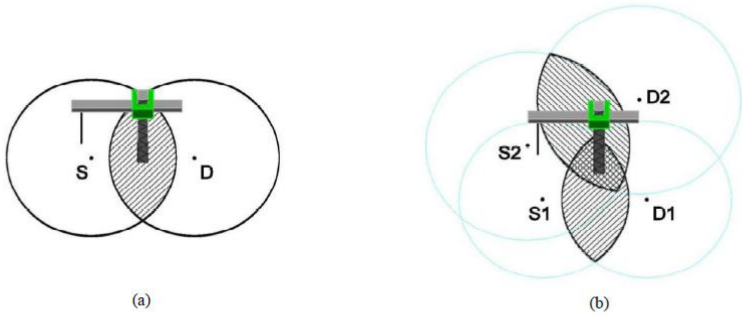

Fig 1: Feasible task area for supply (S) and demand (D) points (a) single task (b) multiple task (adopted from Irizarry and Karan, 1999)

If there is no overlap between tasks, then a single tower is not enough to handle both tasks. The geometric closeness of tasks can be measured by the size of the overlapping area (the larger overlapping area, the greater closeness). A larger overlapping area between two or more cranes may result in longer presence of the cranes in the shared area and therefore there will be a higher risk of collision (Shapira and Simcha, 2009b). Thus, the model searches for places with minimum overlapping area between cranes and their surrounding facilities.

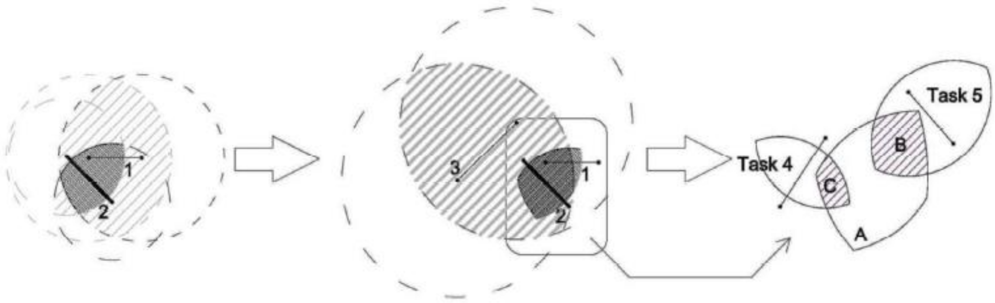

Fig 2: Task closeness (adopted from Zhang et al. 1999)

3. Case Study

In this case study Tower Crane Management on a commercial project in Moscow, Russian Federation is analyzed. The project consists of 420,000 m² GFA (hotel, office buildings and residential with 2 to 3 floors of underground parking). The project was financed by international bank and the Main contract was appointed under cost plus (open book) guaranteed maximum price contract. Time programme was previously agreed, and was exposed to many risks due to challenges in logistics, weather conditions, subcontractor performance and coordination etc.

Employer (Investor) wanted to optimize the crane usage for their maximum benefit and they also wanted it to be dismantled within two months after the completion of concrete works.

Tower cranes are intensively used during structural – concrete works, for vertical transportation of reinforcement, formwork and sometimes for concreting of walls and columns. Construction of underground and above ground is different because of more activities which is performed in parallel with concrete works (waterproofing, excavation, dewatering, protection of foundation pit) below level ±0,00, and programme of works depend on coordination, and technological links between activities. Tower cranes for construction above level ±0,00 are mostly used for concrete works and it is also used for the logistics of other materials for brickwork partitions and façade in parallel depending on the availability. For the optimal use of tower cranes, project phases should be appropriately defined and based on that number of cranes for each phase to be planned.

UNDERGROUND PART

UNDERGROUND PART		Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15	Oct-15	OVERALL
CONCRETE PLAN acc to SVARGO programme		481	3528	6104	7440	7860	8269	7908	6386	6386	6180	4160	**64702**
(o) Number of cranes/month				1.3	3.5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	
average number of people work under crane				91	245	350	350	350	350	350	350	350	
(F1) production with tower cranes				1456	3920	8050	8050	8050	8050	8050	8050	8050	
production with mobile cranes		481	3528	1500									
MAX CONCRETE PLAN acc to CRANE PLAN		**481**	**3528**	**2956**	**3920**	**8050**	**8050**	**8050**	**8050**	**8050**	**8050**	**8050**	**67235**

CONCLUSION : production of around 65,000 m3 in 11 months (8-9 months cranes on site) need 5 tower cranes

Assumptions:
Crane installed on site

crane №1 30-Jan-15
crane №2 20-Feb-15
crane №3 1-Mar-15
crane №4 15-Mar-15
crane №5 1-Apr-15
add crane №1
add crane №2

(A) Optimal number of workers per crane **70**
(B) Winter productivity (m3 concrete/month/worker) **16**
(C) Optimal productivity (m3 concrete/month/worker) **23**

ABOVE GROUND PART	gross area (m2)	Nov-15	Dec-15	Jan-16	Feb-16	Mar-16	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16
Building 6	**22638**			3773	3773	3773	3773	3773	3773				
Building 7	**22627**							3771	3771	3771	3771	3771	3771
Building 9	**6875**									1719	1719	1719	1719
Building 10	**28039**					4006	4006	4006	4006	4006	4006	4006	
Building 11	**34110**	4873	4873	4873	4873	4873	4873	4873					
Slabs / month (m2)		4873	4873	8646	8646	12652	12652	16423	11550	9496	9496	9496	5490
(D) Average production (m2 slab/month)	**9524**												
(F2) Number of cranes according to formula 2	6.3												

CONCLUSON: additional two cranes should be installed

(E) For above ground calculation (m2slab/crane/month) **1500**

FORMULA 1 = (o) * (A)* [(B) or (C)]

FORMULA 2 = (D) / (E)

Table 3 – Number of crane calculation based on concrete plan and proposed production rates

Maximum quantity of concrete planned to be poured monthly on that construction site was 8,000 m³ for the below ground works. Simple calculation based on production rates proposed in the above chart gives us the optimum number of cranes to be used is five with number of people – 350 productive skilled workers to achieve the planned monthly concrete works of 8000 m³. In actual additional 2 cranes were installed to achieve the planned concrete plan.

For the approximate estimation of crane usage duration, planning tools like, Microsoft Project, Primavera, Asta Power Project etc. are used.

According to the contract milestone table and duration, time programme was prepared using software Primavera Enterprise P8.2 with works breakdown structure (WBS) as belowground and above ground. Concrete quantities were loaded as resources, with linear distribution as shown in the fig 3 and histogram of concrete to be poured monthly is obtained. This plan is very similar to one presented in the table 3. Also, the crane allocation is shown in the programme as 'level of effort' activities as separate WBS.

In presented case concrete distribution was distributed as linear, but there is possibility to set distribution as front or back loaded, bell shaped, normal distribution, etc. In the table 3 it's been already presented the concrete plan with crane calculation and number of people required.

Maximum concrete poured per month = number of cranes x number of workers per crane [70] x production/worker/month (calculation on the above part of table 3).

Number of cranes = square meter of slabs poured per month / average production per crane (calculation on the below part of table 3).

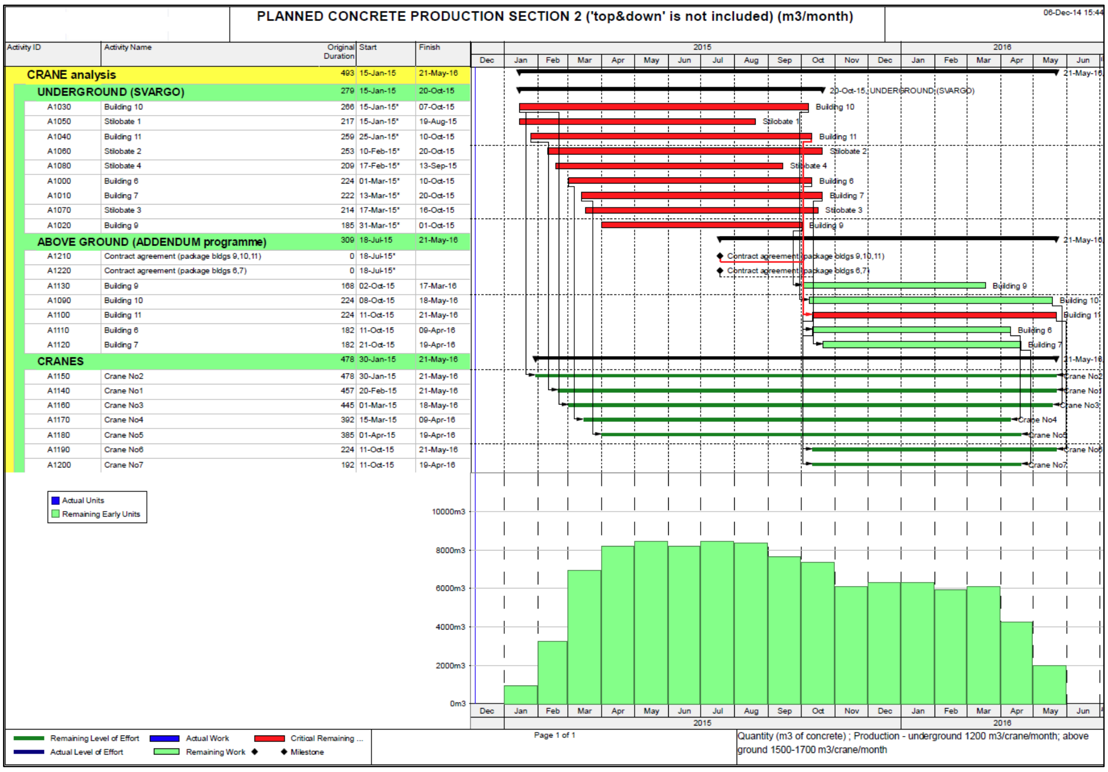

Fig 3 – Planned concrete production and crane loading during concrete works

Generally, in the table 3 and fig 3 shows the same excercise, but for better understanding and presentation it is proposed to calculate concrete plan using planning and scheduling software in fig 3, and then it is exported to Microsoft Excel table, as in the table 3 for the calculation of concerete plan, labor and number of cranes required.

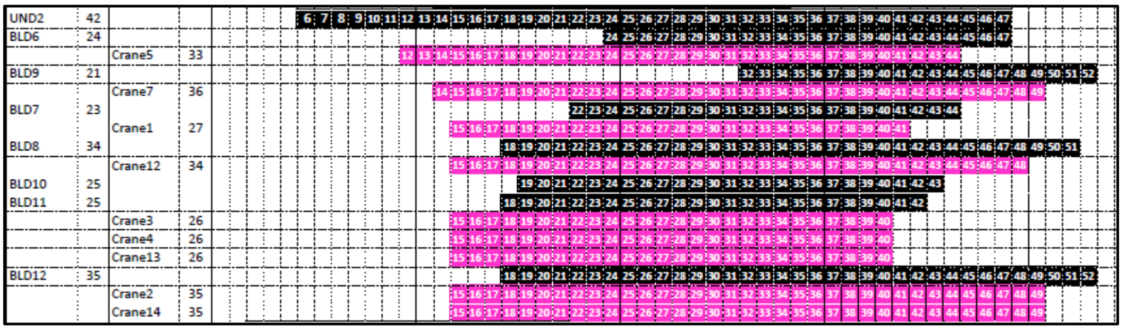

Fig 4 – Time programme and crane engagement per building

On the Fig 4 is shown in black color planned period for construction, and in pink color planned period of crane installation on site, similar presentation as on fig 3.

Renting company proposed number of cranes and layout presented on fig 5. Using methodology of supply and demand points, conflicted areas, and calculation of production rates, it was concluded that number of cranes is very high and there are many conflicted areas between cranes.

A large overlapping area between two or more cranes may result in longer presence of the cranes in the shared area and therefore there will be a high risk of collision between the cranes. Even though with this number of cranes, high productivity is possible, but there will be low percentage in utilization of individual crane. Also, cost of installation and dismantling of cranes in this case is very high. Therefore the crane company's proposal was rejected.

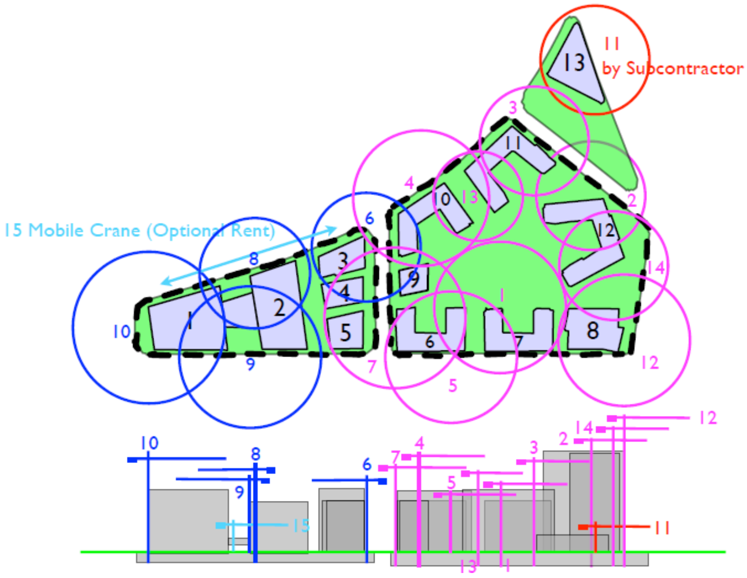

Fig 5 – Proposed crane layout by renting company

For phase 2, which is point of concern in this paper, crane company has proposed nine cranes but according to calculation in table 3 with assumptions sufficient number of cranes to achieve programme is 6,3 (7). General contractor analyzed crane company's layout, position of buildings (demand points), supply points, and proposed the tower crane strategy to achieve the project programme.

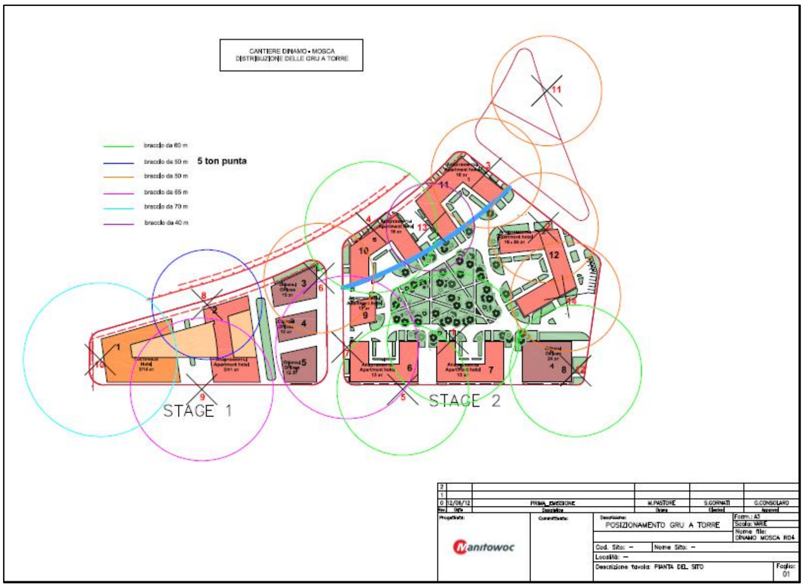

Fig 6 – Proposed tower cranes for commercial project by crane renting company

Calculation in table 4 is overall crane usage on construction site, based on concrete works programme. From that calculation, it is possible to define cost of cranes and to analyse possible solutions for crane usage. That calculation is based on very aggressive approach of cranes being dismantled 2 months after the completion of concrete works.

	CRANES					waiting time (6)-(1)	PROGRAMME SENT TO THE EMPLOYER		
	crane number	start	finish	finish + 60 days	renting period (months)		start	finish	duration (months)
		(1)	(2)	(3)	(4)		(6)	(7)	(8)
Building 6	4	25-Nov-15	2-Jul-16	31-Aug-16	9	39	3-Jan-16	2-Jul-16	6.0
Building 7	5	25-Nov-15	30-Oct-16	29-Dec-16	13	159	2-May-16	30-Oct-16	6.0
	7	3-Jan-16	30-Oct-16	29-Dec-16	12				
Building 9	3						3-Jul-16	17-Dec-16	5.6
Building 10	3	25-Nov-15	17-Dec-16	15-Feb-17	15	97	1-Mar-16	10-Oct-16	7.4
	2	25-Nov-15	10-Oct-16	9-Dec-16	13	97			
Building 11	1	21-Nov-15	1-Jul-16	30-Aug-16	9		21-Nov-15	1-Jul-16	7.4
	6	15-Dec-15	1-Jul-16	30-Aug-16	9				
					80				
Construction period (sum (8))					32				
Addition 2 months* 7 cranes					14				

Zone of 'top&down'								
Building 8	A	1-Aug-15	3-Sep-16	2-Nov-16	15	4-Oct-15	3-Sep-16	11.2
Building 12	B	15-Jul-15	4-Sep-16	3-Nov-16	16	7-Sep-15	4-Sep-16	12.1
	C	15-Aug-15	4-Sep-16	3-Nov-16	15			
					46			

Table 4 – Overall crane engagement per building

After analyzing the proposal from crane renting company (shown on fig 6) and calculation presented in table 3 and construction time schedule, decision has been made to organize vertical transportation with tower cranes, as in fig 7. Although calculation shows it requires only 7 cranes but after expert analysis with all possible assumptions, decision is been made to install 8 cranes for the construction of phase 2. The main reason for installation one additional crane is due to restricted position of supply points, and to be on the safe side in case of any unknown risk and to reduce time for construction. With this strategy utilization of tower cranes has been made higher than average referenced in the literature.

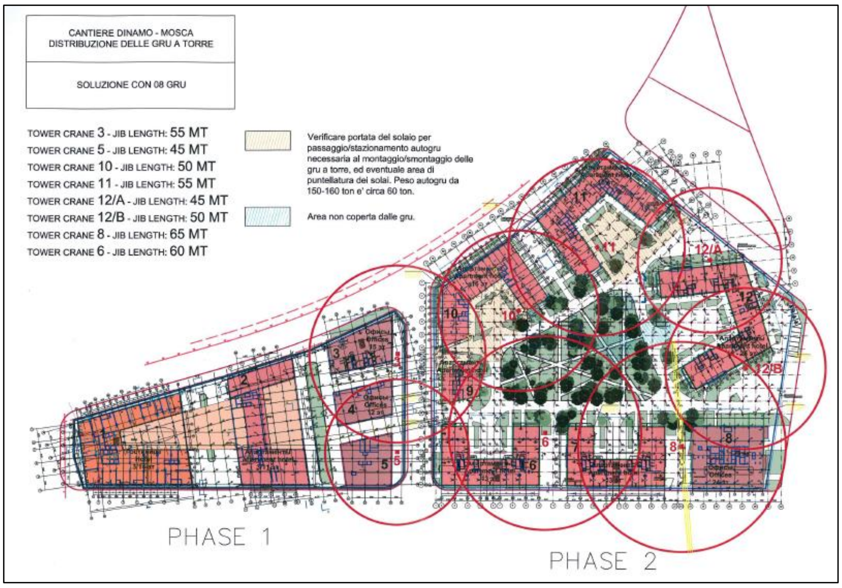

Fig 7 – Construction plan with position of tower cranes for phase 2

4. Conclusion

This overview and analysis is attempt to present and clarify main topics related to crane analysis, calculation and management in high rise construction. Case study based on previous project experience should be analysed and confirmed at the end of the project with statistical data collected during execution period. Proposed approach of number of cranes calculation can be improved with different productivity rates, which depend on specifics of construction site, building type, climate conditions, technological and organizational factors, etc. Right possition of crane should be defined considering supply and demand points, and that is mostly geometrical approach. This problem always should be analysed from planning perspective as productivity and duration of crane usage on construction site make great impact over many aspects of the construction process.

References

Emsley M.W. "A model to optimize single tower crane location within a construction site", *A Doctoral Thesis*, Loughborough University

Irizarry J., Karan E. (2012) "Optimizing location of tower cranes on construction sites through GIS and BIM integration", *Journal of Information Technology in Construction, Vol 17 2012,* pp. 351 – 366

Hasan S., Al-Hussein M., Gillis P. (2010) "Advanced simulation of tower crane operation utilizing system dynamics modeling and lean principles", *Proceeding of the 2010 Winter Simulation Conference,* pp. 3262-3271

Tork A.Z. (2013) "A real time crane service scheduling decision support system (CSS-DSS) for construction tower cranes", A *Doctoral dissertation, University of central Florida*, Orlando, Florida