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POST - EARTHQUAKE RECONSTRUCTION OF THE HISTORIC CITY CENTRE OF L'AQUILA: A PROPOSAL CONCERNING THE RUBBLE TRANSPORTATION PROBLEM

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Abstract. *Post -earthquake reconstruction of the historic city Centre of L'Aquila, Italy, can be considered as the largest building site now under operation in Europe. The earthquake that hit the city of L'Aquila on the 6th April 2009 generated a so-called seismic crater that comprises 56 municipalities and concerns an area of almost 2.400 Km2. The earthquake of 2009 destroyed or severely damaged all historic buildings of the city Centre. Nowadays, in 2020 there are more than 8.000 completed construction projects that produced almost 4.000.000 t of removed rubble. The reconstruction process of L'Aquila has been soon defined as "the biggest construction site of Europe". This experience of managing a huge number of construction projects in the same town highlighted the need of a multi-project coordination of the re-construction activities, and a central co-ordination office has been created. Problems concerning the co-ordination of many construction sites that are located very close to each-other are many and are related to the organization and sharing of different resources: space for tower cranes, access routes for vehicles, space for temporary scaffoldings and space for debris storage and disposal. The programme management of these production resources needs to be based on a General Management plan that is proposed. In particular, the problem of rubble production, transport and storage has been addressed in the plan proposition. In fact, the production, transportation and storage of rubble produced by construction operations can be considered one of the main criteria of the multi-project optimization process needed for the co-ordination of the city reconstruction. As a pilot study, a simulation of project co-ordination of an urban area that includes eleven building blocks under re-construction has been performed with the traditional resource levelling procedure. Therefore, the reconstruction programme schedule of the area has been optimized considering the process constraints due to quantitative limits of rubble transportation and disposal.*

1 INTRODUCTION

Reconstruction following a destructive natural hazard is of paramount importance for human life and built environment. The post - earthquake reconstruction of the historic city Centre of L’Aquila, Italy, can be considered as the largest building site now under operation in Europe. The earthquake that hit the city of L’Aquila on 6th April 2009 generated a so-called seismic crater that comprises 56 municipalities and concerns an area of almost 2.400 Km2. The earthquake of 2009 destroyed or severely damaged all historic buildings of the city Centre. After the seismic event of 2009 the reconstruction phase took place in two times. Firstly, soon after the earthquake, the reconstruction focused on timely interventions of safety works to prevent additional collapses of damaged buildings. After this, in 2010 started the reconstruction process concerning the renovation or reconstruction of damaged and collapsed buildings. Nowadays, in 2020 there are more than 8.000 completed construction projects that caused the removal of almost 4.000.000 t of rubble. The reconstruction process of L’Aquila has been soon defined as “the biggest construction site of Europe” [1]. This experience of co-ordination of a huge number of building project in the same urban area highlighted the need of multi-project coordination of the reconstruction activities and a municipality project co-ordination office has been created [2][3][4]. Therefore, a general construction site plan has been proposed, with the aim of the co-ordination of the thousands of contemporary construction sites under operation [1]. The co-ordination of many construction projects that are located in the same town and near to each-other is needed to manage and share different and scarce resources: space for tower cranes, access routes for vehicles, space for temporary scaffoldings and space for debris storage, transportation and disposal. In particular, the problem of rubble productions, storage and transportation has been addressed in the presented pilot study. A simulation of project co-ordination in an urban area (termed compartment by the municipality project coordination office), composed by eleven building blocks under re-construction has been addressed. The debris production, storage and transportation process has been optimized by application of the traditional multi-project resource allocation process. Considering a specific time frame, the rubble production process can be planned for each construction site. Then the multi-project schedule is optimized considering the quantitative constraints of on-site rubble storage and transportation to the sanitary landfill.

2 THE RECONSTRUCTION OF THE HISTORIC CITY CENTRE OF L’AQUILA

The approach adopted by the Municipality of L'Aquila for the reconstruction of the historic city Centre after the earthquake of 2009 was based on extraordinary regulations that introduced the Reconstruction Plan as an urban planning tool by establishing objectives such as: the socio-economic recovery of the city, the redevelopment of the town and the return of the population to homes damaged by the earthquake [3]. The Reconstruction Plan was defined as a technical tool in order to establish some procedures for the reconstruction. The chosen strategy for the reconstruction of the historic city centre and of the surrounding hamlets, entailed as a first step the definition of the perimeter of the historic city of L’Aquila and of the surroundings. Therefore, various reconstruction areas have been identified. The idea was of favoring the direct and free action of restauration and building rehabilitation of single private owners, without limiting their actions in the framework of the national and local building regulations. The complete overview of the planned and in-progress construction projects of the city was provided by a local project coordination office of the municipality, termed “Supercantieri” [3], [4], [5], [6].

The observation of the complicated development of the reconstruction process of the historic City Centre of L’Aquila [1], has highlighted the need of a General Reconstruction Plan like the one presented by the Municipality of Villa Sant’Angelo, a small town nearby L’Aquila. The General Construction Plan of Villa Sant’Angelo [7] was developed with the aim of satisfying the needs of the owners and of the construction companies that are operating simultaneously for the town reconstruction. A need of coordination, indeed, arises when there are many construction projects operating on nearby sites or in a single building block. For instance, the operating area of tower cranes needs to be planned to avoid clashes and hazards in the interfering areas of the lifting machines. Another case concerns the incorrect positioning of a tower crane in a construction site that can hinder the installation of other construction equipment in the adjacent construction sites.

The proposed general construction plan provides for a series of graphic layouts concerning [7]:

- division of the town into transit areas with the aim of better organizing the layout of construction spaces;
- identification of the entries to the historic center and of the main driveways, with the indication of the minimum roadway dimensions;
- identification of the active construction sites;
- indication of the spaces to be allocated to individual construction sites and their equipment and temporary facilities (cranes, storage areas, scaffolding);
- preparation of a plan for emergencies;
- detailed assessment concerning the dimensions of the roads and the consequent maximum size of the scaffolding that can be installed to allow the passage of vehicles.

Actually, without a detailed general construction plan the post-earthquake reconstruction of L’Aquila was developed not without difficulties. The effect of this was that the choices of the construction projects that first received the state funding and the notice to proceed, may have hindered the process organization of the adjacent construction projects, therefore delaying the execution of the other works.

3 THE GENERAL CONSTRUCTION PLAN OF RECONSTRUCTION: A PROPOSAL

In the research work under this paper, the development of a General Construction Plan for the reconstruction of the historic city centre of L’Aquila is proposed [1]. The aim is to develop an approach and a tool that can give to construction companies and consulting professional the fundamental technical indications to install and operate more efficient and more safe construction projects.

A sector of the central axis of the historic center of the city has been chosen for the proposed pilot application and study. The central axis is an area in the historic city centre of L'Aquila which extends along the main street of the city (Corso Vittorio Emanuele). This is the fulcrum of the city but at the same time the most problematic area, presenting almost all the characteristics of all the historic city centres: narrow streets, structural units of buildings belonging to different historical periods, different construction techniques etc. Then, new earthquake – related characteristics have been added to this: the installation of general safety provisions as large shoring and scaffoldings, the presence of dangerous buildings, of ruins on the ground and in the streets, of hazardous and forbidden areas. In addition to this, the contemporary presence of a multitude of activities and different operators (Fire Brigade and Army forces, private citizens, professionals, a large number of workers, etc.). In order to better manage the reconstruction of the central axis, the Municipality has provided for the subdivision of this area into the so called "compartments", each of which has different dimensions and characteristics [3]. The presented pilot study considers only one compartment (the A9) of the ten of the urban sector (fig.1).

The proposed general construction site plan develops in two parts: a cognitive section and an operational section.

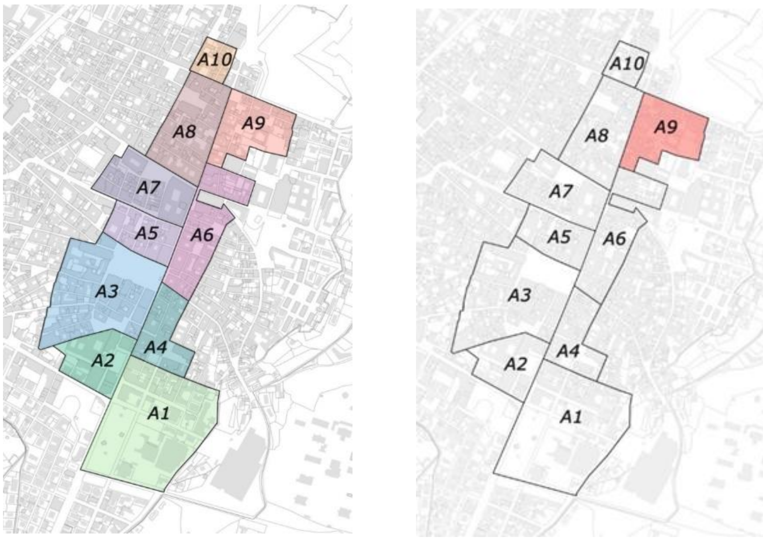

Figure 1: compartments of the old town of L'Aquila [3] [5]

A) Cognitive section. The first step of the cognitive phase involves the identification of the sector within the urban area of the historic city, the mapping of the building aggregates that are inside it and their compliance to building safety standards. After this, the following features are identified: the possible entries to the sector; the direction of travel and the driveways (of which the minimum size is reported). In this way it is possible to establish which roads should be closed because of construction works and which type of vehicles can circulate (fig.2). In analyzing the urban viability, the plan detects the areas that can be used as operational logistic centers for the construction sites of the sector due to their size and accessibility. The same study includes all those areas of reduced dimensions such as internal courtyards, open spaces, small squares that can be used for the installation of any construction equipment and temporary infrastructure. The aim is to produce a complete knowledge of the construction – related characteristics of the urban sector.

B) Operational section. The operational section indicates the provisions relating to the construction sites of the building aggregates. Firstly, the hypothetical positions of the tower cranes of each building aggregate are defined, considering they are all simultaneously operating. The interferences between the cranes are then evaluated: if these are such as not to allow the activities to be carried out simultaneously, a priority of intervention between the construction projects needs to be assessed, eventually indicating which project can start as first the project operations and which has to remain idle or can only start after the completion of the preceding one. Therefore, a sequence of construction operations can be defined because of the priority of installation of lifting equipment, usually indicating two phases of construction: in the first step the predecessor construction projects are executed, in the second step the successor projects starts the operations (figure 3).

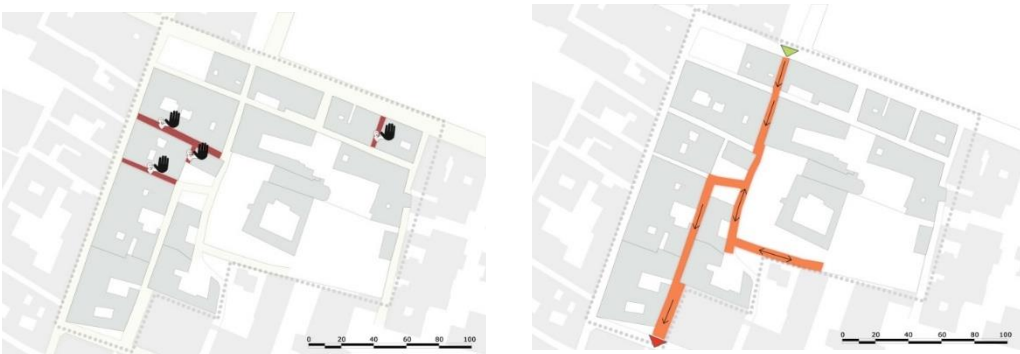

Figure 2: Sample of street categorization inside compartment no. A9

Figure 3: Compartment A9. Tower cranes general plan – phase 1

In the Cognitive section, the definition of the types of scaffolding is of capital importance to allow easy and safe traffic to and from construction sites and to permit the passage of emergency vehicles. Due to the presence of narrow roads, scaffoldings with a short span between the struts at the basis are preferred. The contractors must therefore install scaffoldings that fit the maximum overall basis dimension indicated in the general plan.

When the plan has set the admissible type of scaffolding for each building, the actual width of the roads can be measured considering the space occupied by the temporary provisions. Therefore, the type and size of the vehicles that can transit need be described in the plan. This is very important because the type of roll-off or site boxes for temporary containment of rubble is planned based on the access roadways to the construction site and on the available space on site.

An estimation of the quantity of debris produced by each building block is needed. The quantity of debris produced by construction operations in each building block is of difficult estimation. As a first estimate, it is possible to quantify the rubble produced by each building block depending on the level of damage caused by the earthquake. A research by the “Istituto per le Tecnologie della Costruzione” and the Italian national “Fire Brigades Corps” [8] found that the quantity of debris caused by the Abruzzo earthquake of 2009 can be computed as a percentage of the gross volume of the building depending on the level of damage. As the complete data concerning the level of damage of each building as detected in the survey performed after the seismic event with the AeDES data sheets [9] were not available for the authors, an estimation of the maximum percentage of debris for each condemned building was used based on the results of the Fire Brigades research [8]. Following the procedure proposed by the Fire Brigades, the quantity of rubble produced by each condemned building having the maximum level of damage (L5), is a rate of 1% of the gross volume of the building itself. Therefore, after the having evaluated the gross volume of each building of the block, the quantity of the rubble produced by each construction project can be quantified (table1). Note that it is assumed that the rubble considered is completely produced by the construction project instead of being produced by the seismic event.

Therefore, an evaluation of the space needed for debris storage on site is detected. The number, the size and available dimensions of debris containers (roll-offs) that can be placed on site is then detected, and then the maximum quantity of debris that can be stored before the transportation to the disposal point can be assessed. The number and size of containers depends on the available space on site, on the size of access roadways. The obstruction of roads due to scaffoldings and shoring of buildings and the availability of maneuver area for trucks should be also taken into account.

Figure 4: Building Block A9. Tower cranes general plan – phase 2

With these assumptions and data it is possible to estimate the maximum amount of rubble produced by each building block. Based on these results, it is possible to estimate the size and number of roll-offs required.

4 THE TRANSPORT PLAN FOR RUBBLE DISPOSAL – PROPOSED APPROACH

One of the main problems in the management of post-earthquake re-construction is the disposal of huge quantity of rubble. As before mentioned, L'Aquila had the greatest damage in terms of volume of rubble compared to all the other municipalities of the seismic crater. Approximately, a grand total of 1,500,000 m3 of rubble have been estimated. Two different stages can be identified for the removal of rubble. The first one concerns rubble deriving from earthquake collapses, or safety provisions and demolition of unstable buildings. In this phase the rubble disposal is managed by state-owned agencies, Army – Corps of Engineers etc. The second one entails the disposal of rubble produced by the renovation and rehabilitation projects of private owned buildings, managed by contractors [10]. In the L'Aquila experience of 2009 and after that, in the experience of the seismic events that affected central Italy in 2016, both phases required long waiting times, consequently slowing down the commencement and the duration of re-construction projects. The causes can be found in bureaucratic issues and in the long time needed to find the locations for rubble storage centers. In the L'Aquila case, the rubble deriving from the reconstruction projects of private owned buildings was delivered to 90 collection points of which only 41 were located in the province of L'Aquila. The other ones were located faraway in the Abruzzo region. The distance of the rubble collection points from the historic city is one of the causes of the increase of time needed for reconstruction, and at the same time caused a vehicular overload of roads [6] [7]. On the other hand, the management of the rubble disposal caused by the 2012 earthquake in the Emilia region was considered a success. Only one year after the Emilia main seismic event, 90% of the rubble had been removed. This was possible because the Municipalities had prepared a plan with a precise sequence of operating phases: with a "request to remove rubble" the owners of the buildings were able to report to their municipal administration the presence of rubble; therefore, following an inspection on site by officers, the waste service manager and the municipal administration assessed the quantity and quality of the waste to be removed and planned the specific removal operations, writing them down in a numbered list, so as to establish priorities [11].

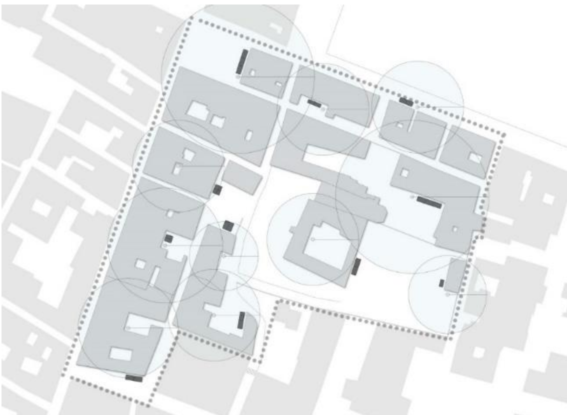

Figure 5: compartment A9. Roll-offs locations

Therefore, it is proposed to apply a new approach to the L'Aquila management method, to be simulated in the case study of the historic city center of L'Aquila. The method is based on the development of the following three strategic choices.

Table 1: rubble quantities evaluation and available storage on site

building block	gross building area (m2)	mean building height (m)	gross building volume (m3)	rubble quantity (m3)	skip dimensions	skip capacity (m3)	skip number	total quantity of rubble storage on site
1	1556	8	12448	125	2,30 x 4,30	6	2	12
2	1753	9	15777	158	1,70 x 3,50	2	2	4
3	866	9	7794	78	2,25 x 3,50	4	2	8
5	1684	9	15156	152	2,30 x 4,30	6	3	18
7	743	9	6687	67	1,70 x 3,50	2	2	4
8	562	9	5058	51	2,25 x 3,50	4	2	8
10	1143	9	10287	103	2,30 x 4,30	6	3	18
11	135	9	1215	12	2,25 x 3,50	4	1	4
12	722	6	4332	43	2,30 x 4,30	6	2	12
13	427	9	3843	38	2,30 x 4,30	6	2	12
14	729	9	6561	66	2,30 x 4,30	6	2	12

4.1 Rubble transfer points

In order to limit as much as possible the vehicles overload of roads, it is proposed to identify a set of temporary transfer points of rubble near the historic center. Each transfer point can collect the rubble coming from a certain number of sectors. In these collecting points rubble from the private owned construction projects will be stored and then transported by larger vehicles to the local collection points identified by the Municipality. The central axis of L'Aquila can be divided into transit areas and for each area a temporary storage site is indicated in the plan. The plan introduces also a transport organization of the travelling paths of each single vehicle that maintains the existing one-way streets and travelling directions that operate before the seismic event. The size and the boundaries of the urban areas have been identified in the plan based on a balance of the distribution of the quantities of rubble of each transfer point. After the identification of the travel paths of vehicles, a traffic analysis of the compartment no. 9, included in transit zone 1 is performed. Therefore, the driveways that connect the compartment with the temporary transfer point are studied. Two different paths are identified based on the positioning of building blocks. The two path are the only possible routes for vehicles used for the rubble disposal.

4.2 Rubble transport organization

The second strategic choice concerns the transport organization: only one vehicle is allowed for each construction site. This provision helps surely the reduction of the environmental impact caused by the traffic of construction vehicles for the reconstruction, but also the following objectives related to the negative aspects of the traffic of construction vehicles in urban areas: a) traffic congestion; b) noise and air pollution; c) car accidents. It should be observed that only in sector 9 the plan indicates the contemporary presence of 11 construction projects in the first phase, and approximately a similar number of projects can be forecasted for all other sectors of the central axis. Therefore, it is clear that the issue of the rubble transport must be addressed with the aim of limiting the traffic in order to manage the rubble removal in a better and safer way. The proposed optimized schedule can be performed with only one vehicle per compartment.

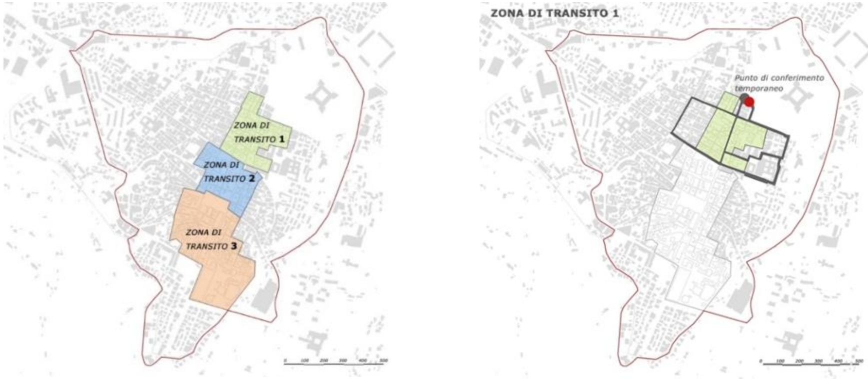

Figure 6: Compartment A9. Transit zone no.1

4.3 Demolition and construction processes management

Finally, the project choices concerning the production of rubble on site is strictly connected to the constraints and decisions previously mentioned. The provision concerning the possibility of using only one vehicle per site, and the available size and number of roll-offs for the rubble storage on site, indicates that a storage limit of debris needs to be set for each construction site as a process constraint. Note that Italian law D.lgs. no. 152/2006 concerning waste management allows a max quantity of 30 cubic metres of waste to be stored on site for a max duration of one year. Therefore, the demolition and construction processes that produce rubble should be optimized for each project, and the number of working crews and their productivity should be planned and scheduled for each working day. This optimization process can be performed with the following steps. Firstly, the type of vehicle and its load carrying capacity needs to be set for each construction project. Then, the lengths of the routes from the site to the rubble transfer point and back to the site should be assessed. The time taken to load / unload the rubble should be estimated, together with the available storing capacity on site. With these assumptions it is possible to determine the maximum amount of rubble that can be produced, stored and transported on each working day and consequently, a multi-project schedule of the demolition phase can be developed.

5 PILOT STUDY

The pilot study considers a simulation of a project coordination activity in the historic city centre of L’Aquila. A compartment that includes eleven building blocks has been considered and a proposed multi-project schedule has been developed with the aim of optimizing the re-construction and demolition processes. The programme schedule, or multi-project schedule, has been developed by optimizing the co-ordination of the single building blocks activities with the traditional resource levelling technique [12]. Therefore, the storage and transportation of rubble that needs to be removed or that is produced on site can be considered a basic criterion for the multi-project optimization process.

Firstly, the programme constraints have been identified for each building block and for each urban area (compartment). The maximum rubble quantity that can be stored on site can be computed by the analysis of the space availability for skips or open-top roll-offs or dumpsters. Therefore, the size and quantity of skips for each size can be assessed (table 1). The project constraints concerning the rubble transportation are then identified. The type of vehicle and their load carrying capacity is indicated in the plan. Therefore, the number of trips per day needed to haul the rubble stored on site can be computed (table 2). Those data indicate the maximum productivity level that can be achieved by each re-construction project.

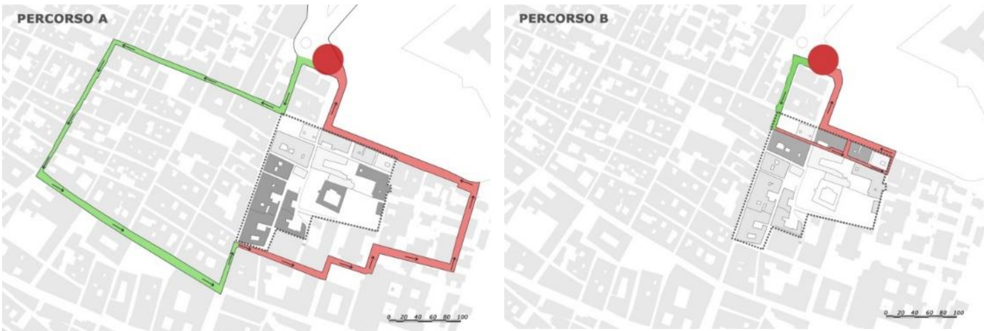

Figure 7: Compartment A9. Travel paths A and B

Table 2: Programme constraints

Constraints per area		**area A9**											
max limit of rubble transportation	*for each area*	*Area A9*											
number of trips	for each area per day	25											
quantity limit per working day	for each area	100											
	building block		***1***	***2***	***3***	***5***	***7***	***8***	***10***	***11***	***12***	***13***	***14***
max storage	*for each building block*												
roll-offs size and quantity	for each building block		12	4	8	12	4	8	12	4	12	12	12
max limit of rubble transportation	*for each building block*												
type of vehicle and load carrying capacit	for each building block		4,7	4,7	4,7	4,7	4,7	4,7	4,7	4,7	4,7	4,7	4,7
number of trips	for each building block		3	1	2	3	1	2	3	1	3	3	3
max quantity per working day	for each building block		*14*	*4,7*	*9,4*	*14*	*4,7*	*9,4*	*14*	*4,7*	*14*	*14*	*14*

Secondly, the duration of project activities can be evaluated. It is assumed that all the rubble to be transported is produced by the demolition of masonry structures for the reconstruction and rehabilitation of building structures. The labor-days needed to complete each demolition activity can be easily estimated. The number of masons allocated to each demolition activity is set depending on the amount of work to be performed. Therefore, the duration of each activity of the project can be evaluated. At the same time, the rubble produced in each working day by each project activity can be estimated (table 3).

The optimization process can be performed with the traditional project resource levelling procedure [12]. The multi-project optimization can be easily solved with the eleven contemporary activities initially performed starting at the same time. The activity network computations produce an output of 46 days to complete the programme, that is the duration of the longest activity (B2) and the critical path (figure 8). The quantity limit of rubble that can be produced per day by the entire multi-project programme can be set by assuming a maximum number of 5 trips of load carrying vehicles. As each small truck can haul 4,7 m3 of rubble, the max quantity per day is 23.5 m3. Then, by shifting non-critical activities with the priority criterion of the max rubble quantity per day the programme levelling can be performed. After only 7 iterations the result is displayed in figure 8. The optimization process levelled the peaks of rubble removal, achieving an even distribution of demolition works always under the max limit of 5 trips per day per compartiment, causing no delays to the total multi-project duration of 46 days.

Table 3: Activity durations and rubble production

Activity number	Activity id.	activity description	measure unit	Rubble quantity	unit price €	sum total €	labor percentage %	labor cost	labor cost per day	men-days	number of workers	activity duration	rubble quantity per day
1	B1	**Building Block 1**	m3	125,00	146,63 €	€ 18.328,75	79%	€ 14.479,71	€ 200,00	72,4	3	**25**	5,00
2	B2	**Building Block 2**	m4	158,00	146,63 €	€ 23.167,54	79%	€ 18.302,36	€ 200,00	91,5	2	**46**	3,43
3	B3	**Building Block 3**	m5	78,00	146,63 €	€ 11.437,14	79%	€ 9.035,34	€ 200,00	45,2	2	**23**	3,39
4	B5	**Building Block 5**	m6	152,00	146,63 €	€ 22.287,76	79%	€ 17.607,33	€ 200,00	88,0	3	**30**	5,07
5	B7	**Building Block 7**	m7	67,00	146,63 €	€ 9.824,21	79%	€ 7.761,13	€ 200,00	38,8	1	**39**	1,72
6	B8	**Building Block 8**	m8	51,00	146,63 €	€ 7.478,13	79%	€ 5.907,72	€ 200,00	29,5	2	**15**	3,40
7	B10	**Building Block 10**	m9	103,00	146,63 €	€ 15.102,89	79%	€ 11.931,28	€ 200,00	59,7	3	**20**	5,15
8	B11	**Building Block 11**	m10	12,00	146,63 €	€ 1.759,56	79%	€ 1.390,05	€ 200,00	7,0	1	**7**	1,71
9	B12	**Building Block 12**	m11	43,00	146,63 €	€ 6.305,09	79%	€ 4.981,02	€ 200,00	24,9	3	**9**	4,78
10	B13	**Building Block 13**	m12	38,00	146,63 €	€ 5.571,94	79%	€ 4.401,83	€ 200,00	22,0	3	**8**	4,75
11	B14	**Building Block 14**	m13	66,00	146,63 €	€ 9.677,58	79%	€ 7.645,29	€ 200,00	38,2	3	**13**	5,08

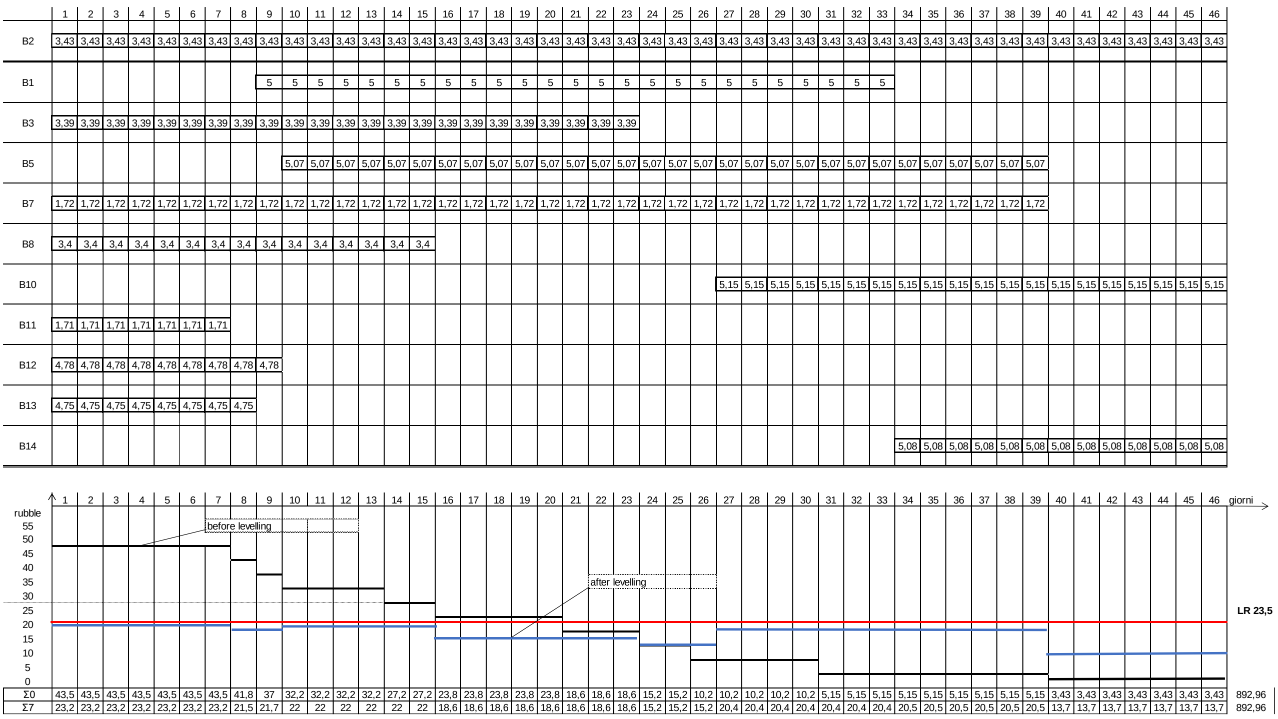

Figure 8: Compartment A9. Schedule optimization procedure

6 CONCLUSIONS

The lesson learned from the re-construction of the historic city centre of L’Aquila has been studied, focusing on the problem of managing a huge number of contemporary building sites in the same location. The study highlighted the need of a multi-project coordination approach of the reconstruction activities that has been implemented by a municipal project coordination office. Anyway, as the co-ordination of many construction sites that are located very close to each-other needs the managing and sharing of different scarce resources: space for tower cranes, access routes for vehicles, space for temporary scaffoldings, space for rubble storage and transportation, a more detailed General Plan is proposed. In particular, the General Plan could address the problem of rubble production, storage and transportation, as a set of basic criteria for the multi-project optimization process. A simulation of project coordination of an urban area that includes eleven contemporary construction projects has been performed with the traditional resource levelling procedure. Therefore, the reconstruction multi-project schedule of the area can be optimized considering the constraint due to quantitative limits of rubble transportation and disposal processes.

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