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Construction Activities Management in Major Accidents Industries: 4D CAD Simulation and Virtual Construction Combined with Genetic Algorithms Use for Identification and Visualization of Workspace Conflicts in an Integrated Decision Support System

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This work addresses the problem arising on all construction sites related to the occurrence of workspace interference between construction activities. In particular the prime objective is to minimize construction risk by using multi-constraint visualization and optimization technologies, taking advantage of new and commercially available CAD technologies that fit in all the main phases of the design and construction workflow. The aim of this paper is on presenting a methodology able to assist site managers in the assignment and identification of workspace conflicts, complying at the same time with the construction activities safety regulations, with a special focus to construction sites having peculiarities such as process industries and major accidents companies (Seveso Directive connected), where construction activities involve a number of safety and constructability issues.

1. Introduction

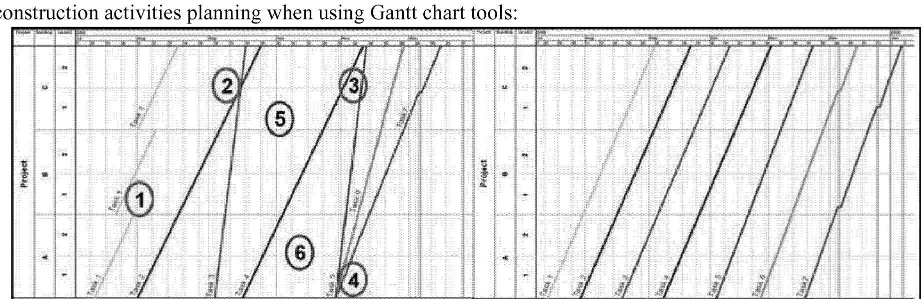
As witnesses of modern society and mindful of past experiences (with statistical data that each year force us to think to these issues), we can affirm that even today control of safety in construction activities to prevent injuries and accidents represents, for involved people at all levels (authorities, designers and construction managers, purchasers, workers, etc.), a challenging issue. The concerted nature of institutes concurring to avoid bad events taking place can be identified both in the regulation framework (differentiated for doctrine and jurisprudence: the former for guidance, the latter for operative regulation) and in the control and surveillance framework (as actuators and witness of provisions enforced by law). Framed the management articulation of problems concerning injuries and accidents during construction activities, it appears to be suitable outlining some considerations on the reasons why construction activities can be indicated as the human production activity having the highest number of injuries and accidents both for quality and quantity. Actors can list the main risk factors that, often combined, lead to accidents: the easiness and the opportunity to enter the construction activities sector, the poor training and the unavailability to hand on correct procedures and best practices, the simplicity the construction activities are often planned and executed with, the poor coordination among teams, companies, productions, etc., the lack of updated documentation in the execution phase and the discrepancy between design and 'for construction' documentation, the unavailability of precise risk analysis (often just files filled for regulation compliance at the beginning of the construction activities without any serious consideration on the specific productions, peculiarities of the site, etc. and forgotten in the archive during the entire construction process). Listed factors (same in the past), as well as more silent risks, forced the lawmaker up in the fifties, to produce specific regulations for injuries and accidents prevention in construction activities. Quoted attentions resulted in general rank normative references in the form of technical rule (e.g. D.P.R. 547/55), as well as more specific regulations for construction activities (e.g. 164/56). Up to now, where, our Country has acknowledged a precise European Directive on workers safety in construction sites (i.e. 92/57/CEE Directive enforced by the Italian D.Lgs. 494/96 and subsequent linked regulations). This in line with the acknowledgment of several other Directives on safety and injuries and accident prevention (see D.Lgs. 626/94, D.Lgs. 334/99, D.Lgs. 238/05). 92/57/CEE Directive became the main milestone in the process for increasing the safety level in construction activities in general. This broad application of this Directive became at the same time the best merit and one of the biggest limits of the regulation itself: in many cases the compliance with the regulation is intended by the actors as the sheer production of documents, in several others the risk analysis and constructability considerations should take into account peculiarities of the construction site, surroundings, adjacent ongoing activities, companies and productions characteristics risks and interferences: the analysis should be intended as a decision support tool dimensioned for the activities, elaborated during design phase (not at the beginning of the construction), kept updated during all the construction phases in order to cover modifications in real time. A number of risks can be avoided with an optimization at design stage of the construction site and productions planning. This approach collides with the figure of the Purchaser: he actually has the main responsibilities for the entire work (independently from eventual subdivisions of it during construction). Responsibilities are shared among several other figures: construction manager, construction activities coordinator, project coordinator, employers, self-employed workers. Discussions on responsibilities of workers (enforced by regulation) during construction activities are out of the scope of this paper. Actors having responsibility are supposed to put in place a series of prevention and protection measures basing on a precise documented risk analysis placed in the main Safety and

Coordination Plan (PSC) and the linked Safety Operating Plans (POS). In the 'fumus' of the reference regulation both of them undertake the rank of risk analysis (PSV for the anticipatory issue and POSs for the specific detail of single production phases). As already stressed by experience for risk assessments non related to construction activities (occupational health and safety enforced by D.Lgs. 626/94 or major accidents prevention enforced by D.Lgs. 334/99 and D.Lgs. 238/05), this analysis is supposed to be included in a management framework to become a real decision support tool (far from the mere documentation tool for regulatory compliance as intended at the first applications of the Decree). In analogy with the HSE management systems the risk assessment in construction activities should become a fundamental step o a safety management system in construction (CSMS, Construction Safety Management System) sites that enforce safety issues since the design phase (optimization of the construction site in consideration of space, surrounding, production processes, employed materials), during the construction phase (incorporating the occurring modifications) and during the decommissioning phase. Actually an effective CSMS can be realized taking advantage of innovative tools that can help the quoted actors overcoming the limits of traditional analysis solutions (in consideration of the complexity of certain construction activities situations) to better analyze risks, clashes, spaces, etc. and to take better informed decision from the incipient planning stage and to maintain the measure of risks during all the construction workflow. Following paragraphs will introduce 'construction activities planning' and 'advanced simulation' techniques as an available route to this 'information rich' approach.

2. Construction activities planning and scheduling

Construction managers coordinate and supervise the construction process from the conceptual development stage through construction, making sure that the project gets done on time and within budget. Actually project planning is a critical task in the management and execution of construction projects. It involves the choice of construction methods, the definition of tasks, the estimation of the required resources, durations for individual tasks, the identification and coordination of any interactions among the different work tasks and use of common resources. In this sense the planning activity is a key point for dealing with safety issues. Trough analysis of the planned and evaluated risks the schedule can be modified: this in particular for specific realities where interferences among subcontractors are one of the critical point of risk analysis. Planning is recognized as an important piece of information by the constructions safety regulation that enforces the inclusion of Gantt in the PSC (Safety Coordination Plan). Actually, in general, the planning process starts with a definition of a Work Breakdown Structure (WBS) for the project. The WBS displays and defines the project to be developed and relates the elements of work to building locations/systems. A WBS establishes a common frame of reference for a construction project. It divides the project into a hierarchical structure of manageable parts or workpackages. The structure enables resource loading of schedules and cost estimations at different level of detail. It is also used to identify parts of the project that can be sub-contracted. Using the WBS planners decompose a project into activities that they associate with one or more building components that make up the project. In addition to assigning dates to project activities, project scheduling is intended to match the resources of equipment, materials and labour with construction work over time. The scheduling process is a challenging task in which planners need to carefully design time-space buffers between activities so that on one hand the productivity for each crew is not slowed by time-space conflicts and lack of work-space and on the other hand the overall schedule is not lengthened due to excessive use of time-space buffers. Actually two different approaches to scheduling are available: activity-based scheduling and location-based scheduling. Activity-based scheduling methods were originally developed for processes that are dominated by complex and sequential assemblies of pre-fabricated components, involving discrete activities on a predestined discrete location. Based on calculating how long it takes to complete essential activities and analyzing how those activities interrelate, this approach provides for a visual and mathematical technique to plan, analyse, schedule and monitor construction projects. The final plan is often presented in a bar chart known as Gantt chart that describes the proposed schedule of the project. Location-based scheduling is not a new concept and has been a research issue for many years. Line-of-Balance (LoB) scheduling technique is, by far, the most known location-based scheduling method. Line-of-Balance is a visual scheduling technique that allows the planner to explicitly account for flow of a project. LoB uses lines in diagrams to represent different types of work performed by various construction crews that work on specific locations in a project. The definition of spatial subdivisions, defined as a Location-Breakdown Structure (LBS), is the backbone of the scheduling and control work with the Line-of-Balance diagram. The definition of a LBS and preparing the building quantities according to this structure goes hand in hand with the definition of the WBS for a project. For the purposes of this paper LoB is the proper tool to analyse a construction problem to identify clashes and safety problems. Figure 1. depicts, in the graphical form of LoB, the most common deviations types that can be easily identified during planning. In LoB diagrams, locations are represented on the Y-axis and project time on the X-axis. The lines represent construction operations by teams. (Left) Common deviation types (no. 1 – 6) in a LoB diagram. (Right) Typical solutions to deviations in a LoB diagram. The association between ‘activities’ and risks can lead to visual identification of clashes that can lead to interferences and injuries/accidents.

Figure 1. Line-of-Balance (LoB),shown using *Vico Control*, to detect problems encountered in traditional construction activities planning when using Gantt chart tools:



1. Same activity in several locations at the same time	- Continuing tasks of equal duration
2. Crossing of activities	- Standard production rate
3. No time and space buffer	- Activities have time and space buffers
4. Several activities start at the same day	- Slacks at start- and end time
5. and 6. inefficient use of time	- Work divided equally over construction time

3. Simulation of complex construction activities in peculiar sites

The methodology and the tools advised by the authors can be based on information and documentation already requested by the regulatory compliance and the construction design process and supported by existing commercially available tools. Actually the methodology enforces a better use of existing documentation during time. In particular the proposed methodology, in line with the most recent regulation (e.g. D.Lgs. 123/2007), becomes a precise tool to better evaluate the occurrence of workspace interference between construction activities that could lead to injuries, or accidents. In particular the prime objective is to minimize construction risk by using multi-constraint visualization and optimization technologies. LoB becomes an efficacious diagramming tool for the PSC and analysis 'in intinere' across all the duration of the construction activities. In particular for construction sites having peculiarities such as process industries and major accidents companies (Seveso Directives connected). Actually the construction activities in this kind of premises (for new process plants construction, modifications of existing plants, revamping activities, etc.) involve a number of safety and constructability issues: those connected with the safety in construction activities laws for health and safety of the workers and also those connected with the fact that often modifications and constructions are conducted with nearby plants running. Layout and spacing in general is a quite critical issue since a crane can hit piping containing toxic chemicals, large vessels containing flammable substances, etc. From a site space planning context, this problem can lead to an inevitable roadblock to the progress of the scheduled construction operations. In real situations, when the spatial congestions occur, they could reduce productivity of workers sharing the same workspace and may cause health and safety hazard issues. The authors focus on the concept of 'visualising space competition' between the construction activities. The concept is based on a unique representation of the dynamic behaviour of activity workspace in 3D space and time (referred to as "4D Simulation"), also basing on the informations coming from the LoB diagrams. Visual 4D planning and scheduling technique that combines 3D CAD models with construction activities (time) has proven benefit over traditional tools (bar charts and network diagrams). In addition to this approach the methodology provides that the initial planning, with particular reference to space employment, would take advantage of simulation on the basis of advanced techniques of optimizazion. Construction site facilities layout planning (FLP), which defines the types, quantities and positioning of the mechanical plants, storage areas and fabrication yards has significant impact on safety, productivity, costs and duration of construction. Although FLP is such a critical process in construction planning, a systematic analysis of construction site layout is always difficult because of the existence of the vast number of trades and inter-related planning constraints, affecting safety in particular. Practitioners of the building industry lack a well defined approach in construction site layout planning, especially for process industry construction sites where problems arise from the peculiarities of these industries also in terms of risks for safety, health and environment. Site conditions, such as the topographical layout, machinery layout and the adjacent environment (e.g. running plants) are unique for each site and strictly connected with the construction activities to be conducted. Consequently, they result in a great variation in site layout strategies and approaches, in order to minimize the risks associated at planning stage. For process industries related construction activities, the allocation of temporary facilities keeps changing and is interrelated with the progress of construction work, which further complicates the planning process. Furthermore the need to deal with existing plants having complex layouts can lead to problems of space. Optimization of FLP (which is a non-linear and discrete system) is difficult, if not impossible, to achieve at planning stage. Hence, FLP of construction sites is usually carried out mainly through human judgement in terms of “constructability changes”. Because of human involvement, there are no conditions that lead consistently to the same result. The objective of this paper is to investigate and analyse the feasibility of using the simulation technology to hybridise the total information of site conditions into a timed visualised model (4D simulation). The produced 4D-model can be analyzed using population techniques produced from a genetic algorithm (GA) model in order to verify an “optimized” layout to generate a virtual site facility layout able to illustrate the objective and the overall risk connected with the construction activities. In site facilities layout optimization against connected risks, there exist many problems to be solved; for example, the nonlinearity of the site facilities layout planning system, the discreteness of the number and positions of facilities, and so on. Among these problems, one of the important issues is the optimal placement of facilities in sites, on the condition that all facilities are considered simultaneously. Genetic algorithms (GAs) are heuristic random search techniques based on the concept of natural selection and natural genetics of a population. Genetic algorithms presume that the potential solution of any problem can be represented by a set of parameters. These parameters are regarded as the genes of a chromosome and can be structured by a string of values, normally in binary form. A positive value, generally known as a fitness value, is used to reflect the degree of "goodness" of the chromosome for the problem. Due to the distinctive features, such as domain independence, non-linearity, robustness and parallel nature, GA has been proven to be a versatile and effective approach for solving optimization problems. From “expert judgement” and “expert algorithms” a construction activities conceptual model can been defined and translated into a 4D-cad representation based on hazard centers identification, vulnerability classes, risks classification and acceptance criteria matrices. Advanced scheduling techniques (i.e. LoB) coupled with the use of optimization solutions (i.e. GAs) actually represent a completely new approach to solve safety issues connected with construction activities management, and, integrated in a desirable CSMS not only guarantee the compliance with the regulations (drafting of the PSC, incorporation of POSs contents from the subcontractors), but become a ‘tool’ to analyse the construction activities flow line during time from the conceptual stage to the decommissioning activities, becoming a real method to control clashes, interferences and safety risks. 4D simulation (connected with LoB) becomes the best agent to visualize the results of the planning and analysis stages during time, taking advantage of documents that construction managers nowadays have at their disposition, however these are not integrated in a unique user-friendly environment. 4D CAD models are typically simply created by linking building components from 3D CAD models with a database and activities that follow from schedules. It provides the user with a clear and direct picture of the schedule intent and helps to quickly and clearly communicate this schedule to different stakeholders in a project, allowing what-if analysis to solve clashes before execution.

4. Benefits

Interpreting the law, for construction sites raising significant safety issues for both injuries and accidents prevention the planning, tuning-up and the realization of a Construction Safety Management System is desirable. This also taking into consideration recognized advancements gained thanks to the application of similarly-built management system (e.g. Safety Management Systems for Major Accidents Prevention, OHSAS 18001 compliant Occupational & Health Management Systems) where they have not been limited to the drafting activity of manuals, procedures, operative instructions. It is a firm belief of the authors that this approach would result in both regulation compliance and benefit in safety issue management. Available technologies could guarantee an effective support in maintaining the CSMS, allowing construction managers to identify risks also during design stage, to solve constructability issues at incipient stage, to evaluate different construction strategies with simulation, to document the decisions to authorities and manage new risks in case of changes during construction. In this sense, taking advantage of Virtual Construction, construction managers can share their experiences and give a realistic impression of the simulated site. This approach allows the authorities to experience the outcomes of the construction managers choices with ease and test alternative scenarios, both in 3D and in 4D simulation environments. 3D visualization technology is appropriate for visualizing and assessing complicated physical construction site constraints in parallel to the determination of construction process flows. Visual 4D planning and scheduling techniques that combine 3D models with time (activities, even by several contractors) have proven benefits over traditional planning tools such as Gantt and Pert chart (enforced by regulations themselves). In 4D models construction managers, end users, employers of subcontracting companies, authorities and other project participants can effectively visualise and analyse problems, clashes, interferences, safety issues that can lead to injuries and accidents, and that are all to several aspects (spatial, sequential and temporal) of construction schedules. As a consequence, more robust (also in terms of greater level of safety) schedules can be compressed after having evaluated several solutions and hence improve safety, productivity and reduce reworks. Actually several commercial tools, taking advantage of both the diffusion of adequate hardware and availability of project documentation in electronic and cad format, can handle large and complex projects during all the phases of construction (in line with the principles of the actuation of the CSMS) and the flexibility to incorporate more construction problems (nD modelling) such has safety costs determination, verification of the influence of surrounding risks (accident scenarios having impact on the construction site), alignment with existing working procedures (e.g. permit to work), etc. In general through the use of Virtual Construction tools, several areas of risk reduction can be achieved also in other stages of the project other than the construction activities, as depicted in the following summarizing table.

Table 1. Advantages of virtual construction tools (courtesy of VICO SOFTWARE, UK)

Advanced 2D	
Electronic drawings management and comparison	Reduce risk of overseeing 2D drawing changes/revisions.
	Better change management.
	Document management system with possibility of integration with existing permit to work system (permits forms have 2D sketches presenting the activity as attachments).
3D (Design)	
Constructability reporting	2D drawings converted to 3D detect clashes and constructability issues prior to getting on site.
Simulations with BIM (Building Information Model)	Fire & evacuation, heat, light, sun studies.
Appreciation of space conflicts	Between hazardous operations and trades on site
Visual communication	3D models are much easier to communicate to non-technical people involved with a project – reducing risk of misunderstanding and allowing studies on escape routes, accessibility and ergonomics. Authorities involvement in the process: better presentation of the safety issues connected with the construction activities.
4D (Location Based & Quantity Driven Planning)	
Enhanced project planning	Quantity driven and location based; more accuracy, more easily. Identification of workspace conflicts arising from incompatibility among productions, materials, from crowding, etc.
Logistical/site feasibility studies	Constructability issues analysis. Plant and equipment, crane positions, materials storage, haulage movements, routes to/from construction site and compatibility with other traffic inside/outside the industrial premise.
Reduction of conflicts	Reduced trade clashes causing delays – these can be visualized in the Flow line™ (LoB) schedule.
Increased predictability	Planned buffers between trades are incorporated, ensuring subcontractors start dates are possible, milestones are achieved and the planned project end date is realized.
Opportunity to optimise	Optimization of location based plan (reduced waste, eliminate poor utilization of locations preserving the separation among conflictual productions, decrease project duration, risk analysis, ensure trade continuity, reduce cost.
Planner focus	Less time spent creating the plan more time communicating – leads to better understanding of project management intent. PSC can easily integrate POSs (taking advantage of custom made templates), Permit to work system can be linked to PSC and Gantt. Analysis of clashes among subcontractor POSs is simplified. PSC and POSs can be kept updated along all the phases of the project, according to the principles of regulations (construction activities safety) and the principles of the adopted CSMS.
Simple 'What-If'	Change large sections of logic with ease due to location based planning.
Improved project control	Superior progress, micromanagement,monitoring and forecasting.
5D (Model Based Cost)	
Increase accuracy	Model based quantities, reduce risk of error in quantity measurement.
Cost tracking / Change management	Reducing risk of budget overrun. Keep updated costs for safety (regulation enforced issue).
Cost management	Understanding and communicating where costs will be/have been incurred.