Health and Safety Design by means of a Systemic Approach

Linking Construction Entities and Activities for Hazard Prevention

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Education and Research in Computer Aided Architectural Design in Europe faces many urgent tasks. Among the Architecture, Engineering and Construction (AEC) international scientific societies, only few researches systematically investigate on how to integrate the design solutions with Health and Safety (HS) planning measures, enhancing a collaborative "fusion" of all involved actors in Design and Construction decision making. Process automation cannot be enhanced until design/management tools, such as Building Information Models, can rely only on entities formalised "per se", geometrical items fulfilled by isolated-object specific information. To face complex problems, BIM models should be able to implement and manipulate multiple sets of entities, qualified by clearly established relationships, belonging to organically structured and oriented (sub-) systems. This paper reports on an early stage research project, focused on the identification of operative rules for Health and Safety design. Implementation on the unique case study of Palazzo della Civiltà Italiana functional refurbishment faces two main objectives: one, more pragmatic, is concerned with boosting workers education about non-standard operative tasks, by means of accurate ad-hoc construction narrative visualisation; another one, more challenging and theoretically complex, consists in modelling "judgment-based" rules, aimed at supporting automated reasoning in Safety Design.

Keywords: *Construction Hazard Prevention, Project construction management and visualization, Health and Safety Management, Risk Modelling, Knowledge Representation*

HEALTH AND SAFETY IN AEC

Education and research in computer aided architectural design in Europe faces many urgent tasks. To correctly decline the most critical aspects of this sector, it must be observed that, compared to other industries, AEC is one of the most hazardous (Carter and Smith, 2006; Wang et al., 2006; Camino et al., 2008).

The issue of safety in workplaces is particularly felt especially in the AEC sector, which still appears to be among the industries the one with the highest number of injuries, with a high fatal accident rate (Eurostat, 2012).

Despite rigorous efforts to improve the constructions working environment in the European Union, the fatal accident rate is approximately 13 workers per 100,000 as against 5 per 100,000 for the all sectors average (Aulin and Capone, 2010).

Italy has the highest rate of workplace accidents and deaths than any other E.U. country. According to Giaccone (2009), the reported work-related accidents for the manufacturing and construction sector for in the year 2008 is 367,132 cases. Giaccone (2009) claimed that these records do not include work-related accidents among undeclared workers, who account for 13.4% of the total labour force, which would contribute to a much higher figure.

Italy, in the overall context of the European Countries, shows one of the highest frequency of accidents, denouncing a certain backwardness on the supervision procedures and the diffusion of prevention. In Italy, according to Ciribini (2010) the poor performances and the lack of managerial skills affecting the construction sites are due to an absence of the co-operation amongst the various actors (Client Organizations, Main Contractors, Sub-Contractors, and Suppliers). Moreover, the current economic situation is worsening the trend and companies are forced to work with low profit margins, trying to save on all aspects of the construction, neglecting the safety.

Designers, architects, engineers and contractors have an influence on the health and safety of building site employees (Gambatese and Hinze, 1999; Behm, 2005; Frijters and Swusste, 2008; Gambatese et al. 2008; Toole and Gambatese, 2008).

From the designers' point of view, there is a different attitude depending on the extent of work to be done: it's well known that for small / medium contracts, safety design is seen as a bureaucratic exercise or, at worst, a matter to be entrusted to experience and habits of business and / or individual workers on the building site.

Conversely, with regard to the works of higher complexity and costs, the need to integrate the design solutions with safety planning measures is realised in few cases. Only sporadically, advanced ICT automated techniques are employed to support the heterogeneous competences and duty required by the Health and Safety Coordinator (HSC) professional profile.

Since the adoption of European Union Framework Directive (89/391/EEC) and the Construction Site Directive (CSD) (92/57/EEC) - in Italy transposed in D.Lgs 81/08 - European building designers are legally required to consider health and safety in their designs.

However, previous studies have shown that designers in general - not just in the construction industry - fall short of satisfying this obligation (Behm, 2005; Fadier and De la Garza, 2006; Frijters and Swuste, 2008); mainly because the most of contractors often neglect the implementation of their health and safety plans (Wang et al., 2006; Saurin et al., 2008).

In addition, the importance of safety economic evaluation is often underestimated: international scientific literature demonstrates that frequently happens that HSC, because of a contextual construction planning uncertainty, ends up with identifying general solutions to fit loosely, without considering any alternative, at comparable cost, even if producing safety improvement measures.

Ultimately, the combination of the inefficiencies between designers and executors leads to an erroneous Safety Evaluation and Estimation, which results in an inefficient use of resources.

PROJECT SAFETY DESIGN AND PLANNING

Safety standards control and management is an extraordinarily resources-consuming task, as it is required to monitor a dynamic 'status quo' of great complexity, which depends on the association and fusion of different professional domains, operating within the context of building sites characterised by heterogeneous risks.

The lack of interest from the companies involved in participating in early stages, before the definition of solutions to apply, lead them to serially reuse devices and working methods, not considering that each site is a unique prototype of himself.

Analysis and causation of accidents and historical data provide valuable but general information for safety planning. Commonly, this information is used to descript textually a possible phenomenon, supported by very accurate statistic charts on probability and risk about the event occurring in a certain operational site area.

Text, charts and evocative pictures are not sufficient to predict when and where accidents occur on unique construction projects. This represents a slowdown of the editing and updating process, a sharp boundary from the point of view of quantity / quality of information provided.

This has led to the advent of information technology enabled approaches for construction safety using virtual designs and simulations of construction operations.

The kind of tool generally used to support these comprehensive competencies includes the class of process management systems and the class of buildings information modelling.

Among the AEC international scientific society, only few researches systematically investigate on how to make a step forward in digital tools to support HSC, enhancing a collaborative "fusion" of all involved actors in Design for Safety.

Research efforts in recent years have focused different approaches for improving site safety with digital models. Khoshnava et al. (2009) stated the main goals as follows:

- to plan and model proactively the sequences of tasks together with the needed safety arrangements and utilities;
- to ensure that all constructions can be built without any safety threat and necessary joints exists for fixing the safety utilities;
- to document planned safety solutions in detail and self-explaining way, and, this information to be conveyed throughout all key players until the last worker in chain.

This paper's work takes off from observing how difficult is trying to design construction safety by means of systems that have been developed for supporting, alternatively, on one side the architectural building design or, on the other side, the construction process management.

INFORMATION MODELLING AND THE ISSUE OF SAFETY IN COMMON PRACTICE

In most advanced economies across the globe, over the last several years, designers started to use Building Information Models, sharing databases in order to be used in synchronous between companies, designers and inspectors.

BIM aims to an efficient exchange of quality information allowing operations systematization, by simultaneously updating objects that describe the project.

BIM-based software packages have well-established positions, and are used by AEC-FM professionals. Such tools also form a natural starting point for BIM-based site layout and safety planning.

The most important BIM software features 3D/4D safety planning, management and communication include: 3D modelling and viewing capabilities, 4D tools and features, tools for analysing risks or safety of the designs and plans, and data exchange capabilities.

Commercial IFC-compliant BIM models allow software interoperability, phase-dependent project analysis, clash detection among components. Recently, in addition to the above capabilities, new platforms have been introduced to platforms to define and manage 4D models. These new environments are focused on assisting Construction Managers in describing the sequence of operations to be performed, by linking a narrative timeline to building entities.

In today's AEC practice for safety planning and management, what can be observed in terms of most common application methods is parallel use of various - non compliant and non interoperable - software.

For instance, site layout drawings or specific illustration about tasks to be performed, are two-dimensional representations, only implicitly linked - just for analogy - to the description of risks, hazards and safety prescriptions of what is expected to happen in reality.

Moreover, with regards to descriptive documents, the use of spreadsheets or pre-designed forms for facilitating data entry procedures, are not adequately supplied by, and linked to, a detailed library and structured databases.

SAFETY REQUIREMENTS AND BIM: STATE OF THE ART

In order to inform different domains actors, eliminate hazard and reduce risks, nowadays, several companies and organisations focused on building information models are researching on the implementation of and the connection to tools oriented to worker's safety training and education, design for safety, safety planning (job hazard analysis and pre-task planning), accident investigation, and facility and maintenance phase safety.

Nowadays, in order to inform the different domains' actors, eliminate the hazards and reduce risks, several companies and organisations have focused on BIM. These companies are investigating how to implement these tools and utilize them for their workers' safety training and education, design for safety, safety planning (job hazard analysis and pre-task planning), accident investigation and facility and maintenance phase safety.

Zhang et al. (2013) and Qi et al. (2011) devised a design for safety tool, making design for safety suggestions available to designers and constructors by formalizing collected design-for safety suggestions and checking the building model.

Bansal (2011) uses GIS based navigable 3D animation in safety planning for predicting places and activities which have higher potential for accidents; he links the information between the CPM schedule and safety recommendation database.

The VTT Technical Research Centre of Finland (2010) developed a manual procedure of using BIM technology for safety planning, management, and communications. As part of the 4D-construction safety planning, VTT visualized BIM-based 4D safety railings for fall/edge protection in Tekla Structures.

In 2010 the Georgia Institute of Technology introduced the first preliminary results of an automated safety rule checker for BIM.

The literature shows that (building) information modelling has enabled virtual safety controls to be used to identify safety hazards.

However, most of the existing efforts in safety planning either largely rely on human input or offer knowledge-based/semi-automated implementation.

Further automation of the tool and better visualization are new options to be explored.

The U.K. Government has commissioned a working group to integrate regulations into BIM in order to simplify compliance [1]. BIM4Regs aims to incorporate Building Regulations, planning and health and safety requirements into BIM models and has been commissioned by the BIM Task Group.

It is being executed by a cross section of government and industry organisations including the Department for Communities and Local Government, the Health and Safety Executive, the planning portal, BRE, software vendors and industry representatives.

Regulatory information will be embedded within BIM software allowing architects and engineers to see if designs comply.

It is important to underline that many rules involve geometrical domain of the representation: for instance, regulations based on minimum distance measurements could be easily incorporated into BIM.

Although P. Caplehorn, chair of the BIM4Regs working group, believes that some 30% of regulations could be easily incorporated into BIM software, the majority of general design requirements fall into the "judgment-based" category.

It will be more difficult to incorporate the "Judgmentjudgement-based" responses to into regulations, since these needs to meet the safety targets.

In order to have a high quality site production plan, all the required arrangements for a site layout model needs to be carefully studied.

Exploring how hazards, risk and solutions might be built into BIM, activating automated reasoning, in a way that designers, constructors and users find useful, is an urgent task to face for international research.

SAFETY REQUIREMENTS AND BIM: POTENTIALS AND LIMITS

Since safety rules, guidelines, and best practices already exist, they can be used in conjunction with existing three-dimensional design and schedule information to formulate an automated safety rule checking system. Safety conditions appear, then are resolved within the construction process, as a project progresses.

Compared to existing BIM application such as clash detection and BIM-based quantity take-off, a basic requirement for a rule-based checking system is that each building object carries information: for example, object name, type, attributes, relationships and metadata including object identification (ID) number, date, and author creating model elements. It is important to point out that the schedule data needs to be linked to the building object data since the assigned protective system needs to be updated accordingly.

There are rule-based platforms available that can apply rules to IFC building model data. Especially the Solibri Model Checker (Solibri Inc.) is one of the software packages that can be used for combining, viewing and examining the content of various BIM-models. This software provides special tools for rule-based automated checking, analysis as well as quantity and other data take-offs. Users can also edit and create new rule sets.

However, effective automation cannot be enhanced until design/management tool can rely only on entities formalised and structured "per se", fulfilled by isolated information.

BIM models should be able to implement and manipulate multiple sets of entities, qualified by established relationships, belonging to organically oriented (sub-) systems. More sophisticated information modelling structures are needed in order to allow querying and computing Design/Construction/Safety entities at a higher levels of abstractions.

Even if the 3D/4D BIM approach is certainly more advanced and valuable than methods and tools traditionally used by HSC, it shows some critical issues:

- classes and detail accuracy of existing parametric entities is oriented mainly to Building design, less to Construction design and not to Safety design. Construction and Safety are still on the fringes of the world of BIM.
- Software manage information not enough structured to model assemblies relations among entities (e.g. hierarchical or topological) or - very critical theme in AEC practice - between building entities (e.g. components, spaces, equipment, machines, etc.) and actors.
- Consequently, 4D BIMs support a low-effective level of rules modelling, with limited possibilities of rule based automatic checking, and still far from "judgment-based" reasoning.

It is believed that the area of “real time project information on safety risks and therefore measures to be taken by the workers" is still a very urgent and open research problem.

HOW TO ENHANCE REPRESENTATION OF SAFETY ENTITIES AND RULES

Authors developed a compact Knowledge Representation Structure, which is able to represent all the concepts involved during the design process, thus improving mutual understanding among all the actors involved and supporting (cross)-domain reasoning: this knowledge structure has been implemented as a Meanings-Properties-Rules ontology template, related to each represented entity.

Depending on the main target of the specific design framework, the universe of the entities included in any kind of design knowledge would have several sets. Referring to the building design these can include spaces, components and furniture. Referring to construction design and these can include phases, activities, actors, operative spaces, building components, formworks, structures, technical installations, machines, context, and so on. Referring to safety design these can include the site equipment, safety railings, guardrails, falling prevention elements, prescription and alert signals, etc.

All concepts considered to be relevant in a design framework are linkable to well defined homogeneous sets of entities by means of suitable sets of relationships.

Any designed object is, or can be, made of entities at different levels of complexity: differently from BIM entities, and IFC classes, the proposed knowledge model allows the formalisation of the relationships that combine entities at a lower level of complexity in more complex one called assembly, in a recursive way.

Any assembly-entity will have a Made-Of relation with its components or, using a formal implementation language, a Has link; in addition, as previously mentioned, it is characterized by a set of its own meanings properties and rules not characterizing its component entities.

By being recursive, even "complex" entities may be constituent parts of other entities having a higher layer of complexity, that therefore are assemblies of assemblies.

By going deeper into the analysis of design and, consequently, in the later stages of it, there is an increasing need to further specify the entities involved and to increase the array of requirements and performance specification necessary to represent each entity.

This kind of increasing specification approach establishes a relationship of father/son kind among the general and specific entities considered, implementable by means of the formal link: Is-A.

For implementing this theoretical model, we are using the ontology technologies in order to model the design entities, physical or abstract, and their space-time relationships structured by means of meanings, properties (defining their state) and rules (relations, reasoning rules, consistency, best practices).

Analysis, checking, evaluation and control of concepts associated to specific entities is performed by means of inferential engines, with deductive 'If-Then' type procedures.

A system of engines -matching rules among the ontologies - will work on a deductive layer overlapped at the actual BIM level, allowing the designers to use in a coherent manner different levels of abstraction, or to exploit a conceptual interoperability.

APPLICATION IN A NON-STANDARD CASE OF STUDY: PALAZZO DELLA CIVILTÀ ITALIANA

Given the state of the art and the potential not yet fully expressed by 4D BIM systems in the field of Health and Safety management, this paper reports about an on-going research that is oriented to formalise Safety Design knowledge based on field experience.

This research is made possible by a particularly positive convergence of two events. In one side, the authors have been contractually designated by Fendi Srl, an international private company known in the fashion sector, for leading Health and Safety Coordination in the challenging functional restoration works of a relevant historical building known as "Palazzo della Civiltà Italiana" (Figure 1), also known as "Squared Colosseum". The company intends to move there its offices headquarter. On the other side, Sapienza, University of Rome assigned to the authors a research fellowship grant in order to investigate on HS support systems.

Figure 1
Palazzo della Civiltà Italiana, 2014

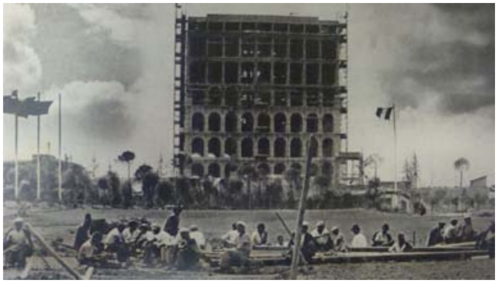

Figure 2
Palazzo della Civiltà Italiana, 1940

This public property is an iconic building of particular historical interest and protected by the Minister of Cultural Heritage rules. In 1935 a design competition was established in order to have this building for the 1942 World Exhibition. The Palazzo was designed by the architects G. Guerrini, E. B. La Padula and M. Romano and constructed between 1938 and 1943 (Figure 2). It was inaugurated in November 1940 as the centrepiece of the Esposizione Universale di Roma neighbourhood (EU42) and continues to be its most iconic building. The structure is also considered one of the most representative examples, in the modern history of architecture, of rational synthesis of classical linguistic elements.

The Squared Colosseum consists of a box that stands on a wide base connected to the street level by two opposing staircases. The scale is imposing: the base covers an area of 8,400 square meters, and the building has volume 205,000 cubic meters with a height 68 meters (50 meters from the base; each level is 8 meters high).

The four faces of the prismatic solid, covered with slabs of travertine stone, are characterized by the strong rhythm of the arches in sequence (nine repeated openings for six floors), strong architectural motif that makes it instantly recognizable as one of the symbolic monuments of Rome.

Main objective of this sophisticated intervention is to ensure, in respect of the triad Time - Cost - Performance, a product of high architectural quality, performed in compliance with the history of the building, planning the work phases in such a way to make them closer to serial standards of production.

In this context, complicated by the need to protect the finish and the existing structures, specialist workers are going to assemble the technical elements for the construction of mezzanines, 4 meter high, and interior sub-structures built with the technology of steel and glass in order to frame the enormous open space in more functional human scale ones.

It seemed immediately necessary to arrive at a real fusion between the design solution for architectural model of the project, the protection of the listed building, the implementation of safety measures, allowing a continuous exchange / upgrade information between architectural design, project and construction site safety.

METHODOLOGY IMPLEMENTATION PATH

The overall research aim is to develop a method for enhancing the quality of information modelled/managed and defining an implementation path toward a desirable dynamic and holistic knowledge-based support system.

Acting in the context of this unique case of study, by applying a reverse engineering approach, it is being possible to benefit from this on-going significant field experience for pushing the limits and potentials of exploring the existing systems.

This paper reports on an early research work oriented to define and implement a systematic methodology for helping in HSC activities, namely to calculate the safety-related performance of a project, providing a consistent basis for comparisons between different safety design solutions.

The main objectives can be subdivided in two levels:

- The first is targeted at educating workers about non-standard operative tasks;
- another one, more theoretically complex, oriented to model "judgment-based" rules, aimed at supporting automated reasoning in Safety Costs' Evaluation and Estimation.

On one side, a 4D BIM-based site plan is being modelled and used to produce illustrative representations of the site organisation and of the safety arrangements.

The 3D views together with 4D narrative, can be used for orientation of site workers, task guidance and instructions, for informing about risks.

On the other side, to manage safety solutions, both predicting during the building design phase and evaluating - in real time - during the construction phase, we are formalising few representative rules to be checked by the system and some related operative actions to be suggested consequently.

In order to have automatic judgement, as a starting task a clear definition of rules to be checked is needed. Specifically, in the safety design phase we are trying to address the prevention of hazard as a case study.

According to the Italian D.Lgs. n.81/2008, inheriting EU Directive (CSD) (92/57/EEC), safety risk assessments are function of physical entities on one side and, on the other side, they can be linked to more abstract coordination process activities.

Primarily, we analysed how to represent a safety condition in terms of objects, attributes and relations needed. Afterwards we formally defined a routine to run the risk evaluation, intended as complex rules to be applied to the objects, attributes and relations involved.

The formal representation of Safety categories and rules to be applied have been implemented by using a compact Knowledge Representation Structure and managed by an ontology based technological pipeline developed by the authors.

In order to assist human decision makers in safety planning and scheduling activities, the outcome of the hazard prediction assessment is an automatically generated alert which would inform the necessary parties.

Future work will be oriented to implement the reporting delivery and the safety solution suggestion, for instance by recommending correct geometry, location, materials and time of installation of the protective equipment that must be installed to prevent a hazard.

FORMALISING DIFFERENT LEVEL OF SAFETY DESIGN KNOWLEDGE

In order to avoid a typical limitation in the evaluation of health and safety risks, authors implement by means of the previously presented knowledge modelling approach, some classes of a more general Health and Safety design ontology.

"Judgement based" evaluation can be performed by using quantitative indicators formalised by Gangolells et al. (2010), which are based on data available in the project documents/models. Indicators measure physical property values of construction/safety related entities, not available in current

BIM/IFC models.

The implementation steps are namely:

1. Represent Safety Risk related to Construction Activity (e.g. expressed in OWL language by means of ontology editors, e.g. Protégé)

2. Represent an extended library within BIM of construction/safety related entities (by means of API), with special emphasis of Risk Indicator physical properties

3. Link Construction Activity (time/space instantiated) with actual BIM/IFC safety related entity (e.g. in Autodesk Navisworks).

After the previous steps are successfully implemented, the system will allow safety designer and HS decision-makers, by supporting them automatically calculating Risk Indicator of the instantiated project Construction Activities.

The proposed ontology will allow the classification of all the terms (aspects, impacts, risks, and procedures) related to the Health and Safety "judgement based" evaluation as well as the relationships that exist among sets of design objects.

Then again, each class will be enriched with different properties which will be used by the decision-making tool to identify the main significant Health and Safety conditions in each design/construction process, and moreover, to evaluate their impact in a specific construction project in order to provide procedures.

DISCUSSIONS AND FUTURE WORK

Safety planning can be a part of 4D production planning. This can create a safety planning practice that is undertaken earlier than traditionally in construction projects, and furthermore it can capture a more detailed planning level (Figure 3).

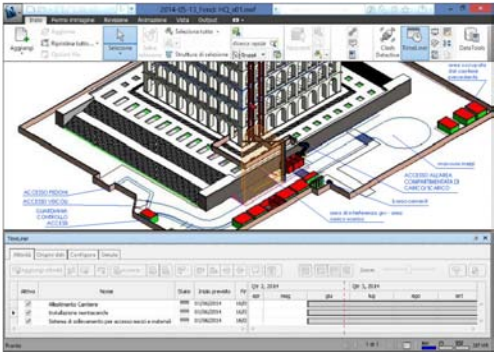

Figure 3
4D BIM logistics model

A BIM-based site plan can be used to produce illustrative representations of the site and safety arrangements, and the views can be used for orientation of site workers, task guidance and instructions, for informing about risks.

Safety control and evaluation is based on both proactive and reactive performance indicators relying on percentage of safe work packages and actual accident data.

The proposed methodology and implementation path is oriented to support designers and construction planners in visualizing and evaluating Safety Risks, related to construction activities by means of Risk indicators.

Vice versa, safety designers need to spend more resources in order to utilize the construction work breakdown structure and therefore enhancing the geometric model with construction/safety related entities by including more details which will be resulting an ever-changing work site schedule.

In summary, the research expected general results are a step forward towards:

- Enhancing safety related detail of the BIM which is typically modelled by the project designers. Specifically: accuracy of construction site entities and building construction sub/phases linked to Safety work breakdown structure.

- A reusable safety knowledge model, introducing a system of hierarchical relationships in time and space for representing parametrical Safety conditions.

- Establish relationships between activities and tasks, hierarchizing relationships between operators and devices and / or safety equipment.
- Predict site hazard and define corrective measures by means of a stored library populated by alternative resolutions. Support HS design by proposing realistic solutions to resolve the identified issues.

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