試就下列兩篇論文，任選一篇，寫出 500 字以內之論文評析。

(一) Modification of a generalized three-dimensional Hoek–Brown strength criterion

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1. Introduction

Researchers have developed different strength criteria for rock [1–9]. Of these different strength criteria, the Hoek–Brown strength criterion has been used most widely. The Hoek–Brown strength criterion was developed specifically for rock materials and rock masses, and its input parameters can be determined from routine unconfined compression tests, mineralogical examination, and discontinuity characterization [4]. It has been applied successfully to a wide range of intact and fractured rock types during the past three decades.

The Hoek–Brown failure criterion, however, does not take account of the influence of the intermediate principal stress, although much evidence has been accumulating to indicate that the intermediate principal stress does influence the rock strength in many instances. Therefore, researchers have developed 3D versions of the Hoek–Brown strength criterion. The 3D versions of the Hoek–Brown strength criterion have advantages over other existing 3D non-Hoek–Brown type strength criteria in that they use the same input parameters as the widely used Hoek–Brown strength criterion [1,2,17,20]. Of the 3D Hoek–Brown strength criteria, only the Zhang–Zhu criterion predicts the same strength as the original Hoek–Brown strength criterion at both triaxial compression and extension states; but due to the non-smoothness of the failure surface at both triaxial compression and extension states and the non-convexity of the failure surface at the triaxial extension state, the Zhang–Zhu criterion may have problems with some stress paths and cause inconvenience in numerical applications
(see next section about more detailed review of the Hoek–Brown strength criterion and different 3D Hoek–Brown strength criteria).

In this paper, the generalized 3D Zhang–Zhu criterion was modified by applying three Lode dependences to address the problem of non-smoothness and non-convexity. The modified criteria were then used to analyze both intact rocks and jointed rock masses.

The modified criteria not only keep the advantages of the generalized Zhang–Zhu criterion, but solve the non-smoothness and non-convexity problem without loss of accuracy for strength prediction.

2. Hoek–Brown strength criterion and its 3D versions

This section describes the Hoek–Brown strength criterion and its 3D versions and performs a brief evaluation of these strength criteria, which provides the background information for modification of the generalized Zhang–Zhu criterion in next section.

2.1. Original Hoek–Brown strength criterion

The Hoek–Brown strength criterion was originally developed for intact rock and then extended to rock masses. The process used by Hoek and Brown in deriving their strength criterion for intact rock was one of pure trial and error. Apart from the conceptual starting point provided by the Griffith theory, there is no fundamental relationship between the empirical constants included in the criterion and any physical characteristics of the rock. The justification for choosing this particular criterion over the numerous alternatives lies in the adequacy of its predictions of the observed rock fracture behavior, and the convenience of its application to a range of typical engineering problems [10].

For intact rock, the Hoek–Brown strength criterion may be expressed in the following form

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_i \frac{\sigma_3}{\sigma_c} + 1 \right)^{0.5} \tag{1}$$

where σ_c is the unconfined compression strength of the intact rock; σ_1 and σ_3 are respectively the major and minor effective principal stresses; and m_i is a material constant for the intact rock, which depends upon the rock type (texture and mineralogy) as tabulated in Table 1.

Table 1
Values of parameter m_i for different rocks [1, 2, 33, 34].

Rock type	Class	Group	Texture			
			Coarse	Medium	Fine	Very fine
Sedimentary	Clastic		Conglomerate (21 ± 3)[a] Breccia (19 ± 5)	Sandstone 17 ± 4	Siltstone 7 ± 2 Greywacke (18 ± 3)	Claystone 4 ± 2 Shale (6 ± 2) Marl (7 ± 2)
	Non-clastic	Carbonate	Crystalline limestone (12 ± 3)	Sparitic limestone (10 ± 2)	Micritic limestone (9 ± 2)	Dolomite (9 ± 3)
		Evaporite		Gypsum 8 ± 2	Anhydrite 12 ± 2	
		Organic				Chalk 7 ± 2
Metamorphic	Non-foliated		Marble 9 ± 3	Hornfels (19 ± 4) Metasandstone (19 ± 3)	Quartzite 20 ± 3	
	Slightly foliated		Migmatite (29 ± 3)	Amphibolite 26 ± 6	Gneiss 28 ± 5	
	Foliated[b]			Schist 12 ± 3	Phyllite (7 ± 3)	Slate 7 ± 4
Igneous	Plutonic	Light	Granite 32 ± 3 Granodiorite (29 ± 3)	Diorite 25 ± 5		
		Dark	Gabbro 27 ± 3 Norite 20 ± 5	Dolerite (16 ± 5)		
	Hypabyssal		Porphyrie (20 ± 5)		Diabase (15 ± 5)	Peridotite (25 ± 5)
	Volcanic	Lava		Rhyolite (25 ± 5) Andesite 25 ± 5	Dacite (25 ± 3) Basalt (25 ± 5)	Obsidian (19 ± 3)
		Pyroclastic	Agglomerate (19 ± 3)	Breccia (19 ± 5)	Tuff (13 ± 5)	

[a] Values in parenthesis are estimates.
[b] These values are for intact rock specimen tests normal to bedding or foliation. The value of m_i will be significantly different if failure occurs along a weakness plane.

For jointed rock masses, the general form of the Hoek–Brown criterion, which incorporates both the original and the modified forms, is given by

$$\sigma_1 = \sigma_3 + \sigma_c\left(m_b\frac{\sigma_3}{\sigma_c} + s\right)^a \tag{2}$$

where m_b is the material constant for the rock masses; and s and a are constants that depend on the characteristics of the rock masses. Hoek and Brown [11] proposed a set of relations between the parameters m_b, s and a and the 1976 version of Bieniawski's Rock Mass Rating (RMR), assuming completely dry conditions and a very favorable (according to the RMR rating system) discontinuity orientation:

(i) Disturbed rock masses

$$m_b = \exp\left(\frac{\mathrm{RMR}-100}{14}\right)m_i \tag{3a}$$

$$s = \exp\left(\frac{\mathrm{RMR}-100}{6}\right) \tag{3b}$$

$$a = 0.5 \tag{3c}$$

(ii) Undisturbed or interlocking rock masses

$$m_b = \exp\left(\frac{RMR-100}{28}\right)m_i \tag{4a}$$

$$s = \exp\left(\frac{RMR-100}{9}\right) \tag{4b}$$

$$a = 0.5 \tag{4c}$$

Eqs. (3) and (4) are acceptable for rock masses with RMR values greater than about 25, but do not work for very poor rock masses since the minimum value which RMR can assume is 18 for the 1976 RMR system and 23 for the 1989 RMR system. In order to overcome this limitation, Hoek [12] and Hoek et al. [13] introduced the Geological Strength Index (GSI). The relationships between m_b, s and a and GSI are as follows:

(i) For GSI > 25, i.e. rock masses of good to reasonable quality

$$m_b = \exp\left(\frac{\mathrm{GSI\text{-}100}}{28}\right)m_i \tag{5a}$$

$$s = \exp\left(\frac{\mathrm{GSI\text{-}100}}{9}\right) \tag{5b}$$

$$a = 0.5 \tag{5c}$$

(ii) For GSI < 25, i.e. rock masses of very poor quality

$$m_b = \exp\left(\frac{\mathrm{GSI}-100}{28}\right)m_i \tag{6a}$$

$$s = 0 \tag{6b}$$

$$a = 0.65 - \frac{\mathrm{GSI}}{200} \tag{6c}$$

Hoek et al. [14] proposed new relationships between m_b, s and a and GSI by introducing a new parameter D, which is a factor that depends on the degree of disturbance due to blast damage and stress relaxation. The values of D range from 0 for undisturbed in situ rock masses to 1 for very disturbed rock masses. The guidelines for selecting D can be found in Hoek [15].

$$m_b = \exp\left(\frac{GSI-100}{28-14D}\right)m_i \tag{7a}$$

$$s = \exp\left(\frac{\mathrm{GSI}-100}{9-3D}\right) \tag{7b}$$

$$a = 0.5 + \frac{1}{6}\left[\exp(-\mathrm{GSI}/15) - \exp(-20/3)\right] \tag{7c}$$

It is noted that the distinction between disturbed and undisturbed rock masses is dropped in evaluating the parameters m_b, s and a from GSI. This is based on the fact that disturbance is generally induced by engineering activities and should be allowed by downgrading the values of GSI.

2.2. Three-dimensional Hoek–Brown strength criteria

A major limitation for the Hoek–Brown strength criterion is that it does not consider the effect of the intermediate principal stress, although it has been found that the intermediate principal stress influences the rock strength in many instances [6–9,16–19]. Therefore, researchers have developed 3D versions of the Hoek–Brown strength criterion. The 3D versions of the Hoek–Brown strength criterion have advantages over other existing 3D non-Hoek–Brown type criteria in that they use the same input parameters as the widely used Hoek–Brown criterion. The following briefly describes several 3D Hoek–Brown strength criteria.

2.2.1. Pan-Hudson criterion

Pan and Hudson [17] proposed a 3D version of the original Hoek–Brown strength criterion for rock mass (Eq. (2) with $a=0.5$), which is expressed as

$$\frac{9}{2\sigma_c}\tau_{oct}^2+\frac{3}{2\sqrt{2}}m_b\tau_{oct}-m_b\frac{I_1}{3}=s\sigma_c \tag{8}$$

where τ_{oct} and I_1 are, respectively, the octahedral shear stress and the first stress invariant defined by

$$\tau_{oct}=\frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \tag{9}$$

$$I_1=\sigma_1+\sigma_2+\sigma_3 \tag{10}$$

in which σ_1, σ_2 and σ_3 are, respectively, the major, intermediate and minor effective principal stresses.

2.2.2. Generalized Priest criterion

Priest [20] developed a 3D version of the generalized Hoek–Brown strength criterion (Eq. (2)) by combining it with the Drucker–Prager criterion, which is expressed by

$$J_2^{1/2}=AJ_1+B \tag{11}$$

where A and B are empirical parameters; $J_1=I_1/3$ is the mean effective stress; and J_2 is the second deviatoric stress invariant defined by

$$J_2=\frac{1}{6}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right] \tag{12}$$

Since the 3D stress state satisfying the generalized Hoek–Brown strength criterion (Eq. (2)) is (σ_1, σ_3, σ_3), the strategy is to determine parameters A and B for the Drucker–Prager failure surface that intersects the Hoek–Brown failure point (σ_1, σ_3, σ_3). With parameters A and B determined, the strength σ_{zf} for an element of material subjected to a general state of 3D stresses $\sigma_x\neq\sigma_y\neq\sigma_{zf}$ can then be predicted. This process is equivalent to the well known process identifying the Drucker–Prager parameters that give the circumscribed fit for the Coulomb strength criterion. Priest [20] originally suggested a numerical procedure for determining parameters A and B and strength σ_{zf}.

Melkoumian et al. [21] later developed an explicit solution for determining strength σ_{zf} at intermediate and minor principal stresses σ_x and σ_y, which is summarized below

$$\sigma_{zf}=3\sigma_p+\sigma_c\left[\frac{m_b\sigma_p}{\sigma_c}+s\right]^a-(\sigma_x+\sigma_y) \tag{13}$$

in which

$$\sigma_p=\frac{\sigma_x+\sigma_y}{2}+\frac{-E+\sqrt{E^2-F(\sigma_x-\sigma_y)^2}}{2F} \tag{14}$$

where $E=2C^a\sigma_c$, $F=3+2aC^{a-1}m_b$, $C=s+\frac{m_b(\sigma_x+\sigma_y)}{2\sigma_c}$.

2.2.3. Zhang–Zhu criterion

Zhang and Zhu [1] proposed a 3D version of the original Hoek–Brown strength criterion for rock mass (Eq. (2) with $a=0.5$) by combining the general Mogi [16] criterion and the Hoek–Brown strength criterion, which is expressed as

$$\frac{9}{2\sigma_c}\tau_{oct}^2+\frac{3}{2\sqrt{2}}m_b\tau_{oct}-m_b\sigma_{m,2}=s\sigma_c \tag{15}$$

where τ_{oct} is the octahedral shear stress as defined by Eq. (9), and $\sigma_{m,2}$ is the mean stress defined by

$$\sigma_{m,2}=\frac{\sigma_1+\sigma_3}{2} \tag{16}$$

2.2.4. Generalized Zhang–Zhu criterion

Zhang [2] proposed a 3D version of the generalized Hoek–Brown strength criterion (Eq. (2)) by modifying Eq. (15), which is expressed as

$$\frac{1}{\sigma_c^{(1/a-1)}}\left(\frac{3}{\sqrt{2}}\tau_{oct}\right)^{1/a}+\frac{m_b}{2}\left(\frac{3}{\sqrt{2}}\tau_{oct}\right)-m_b\sigma_{m,2}=s\sigma_c \tag{17}$$

where τ_{oct} and $\sigma_{m,2}$ are, respectively, the octahedral shear stress and the mean stress defined by Eqs. (9) and (16).

2.3. Brief evaluation of 3D versions of Hoek–Brown strength criterion

The (generalized) 3D Zhang–Zhu criterion predicts the same strength as the two-dimensional (2D) Hoek–Brown strength criterion at both triaxial compression ($\sigma_2=\sigma_3$) and extension ($\sigma_1=\sigma_2$) stress states; but the 3D Pan-Hudson criterion does not predict the same strength as the Hoek–Brown criterion at either triaxial compression or extension stress state. Since the 3D Priest criterion is derived by identifying the Drucker–Prager parameters that give the circumscribed fit for the Hoek–Brown criterion, it predicts the same strength as the Hoek–Brown strength criterion at triaxial compression stress state but not at triaxial extension stress state [1,2]. So the (generalized) 3D Zhang–Zhu criterion tends to provide better strength predictions, especially at the triaxial compression and extension stress states. However, it is noted that the (generalized) Zhang–Zhu criterion envelope is not smooth at either the triaxial compression or extension stress state and concave at the triaxial extension stress state, which may lead to problems with some stress paths and cause inconvenience in numerical applications [1,2].

(二)

Integrating resource production and construction using BIM

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1. Introduction

Industrialization in construction started several years ago [1] and is an important trend in the construction industry, aiming to achieve several improvements in the sector like higher productivity levels and better quality of construction products. Reports and case studies from different parts of the world have shown that prefabrication and on-site assembly are becoming common practice [2,3]. Industrialization is trying to address the problems of low profit margins in comparison to other industries, and a shortage of skilled workers [4,5]. Prefabrication of building components at a remote facility is shown to save space for material storage on site, assures better quality control of part production, reduces waste and enables reengineered and more efficient supply chain management.

However, industrialization of the construction process requires a high level of automatization. At this point, the construction industry faces many problems, especially as far as handling of information and integration of data and information systems are concerned. As pointed out by Johnsson [2], ICT tools for construction do not support automated manufacturing, and tools developed for the manufacturing industry lack support for structural design and detailing. In our research, we focused on the mapping between unconnected data structures and models in such heterogenous environment.

The work described in this paper is a result of an industry-led research. The initiative for the work came from a Slovenian manufacturing and construction company that introduced industrialized construction several years ago. The above mentioned research problem originates from everyday activities of the company, which is trying to improve project progress tracking and resource management in multi-project environment. This resulted in an R&D project, which includes work process analysis, synthesis of common information needs for all building design and construction processes and development of data transformations needed to overcome the identified gaps in the flow of information.

2. Work process analysis

The company is medium-sized and is involved in several projects both in Slovenia and abroad. Primarily it produces storage house buildings, industrial halls and large store buildings. The buildings consist of load-bearing steel or concrete construction and are closed with metal roof and façade elements. In addition to the construction projects, the company also manufactures roof and façade elements for the market.

Our work started with an analysis of project workflows after the project contract is signed, given that pre-sales and pure manufacturing processes are well organized and appropriately supported by ICT tools. From a project viewpoint, the work processes at the company can be divided into three groups — (1) detailed design, (2) prefabrication and (3) construction site activities. *Detailed design* takes input from customer requirements and architectural design and has two outputs. It is the basis for manufacturing and it also produces blueprints for construction. The work is well supported by CAD tools for both load-bearing construction design and façade elements design. *Prefabrication* is organized as mass production and is highly automated. Industrialized production of building elements is integrated with other business activities such as sales, purchasing and logistics via the Enterprise Resource Planning (ERP) system. *Construction site activities* are project

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related and include organization of the construction site, construction works, project progress monitoring and management activities, and tracking of material flows to and on construction sites. The analysis has shown that this group of activities is not sufficiently supported by ICT tools. Detailed planning and data collection concerning the performed construction works were handled inconsistently, with several software tools depending on an individual project manager.

Prefabrication and construction processes run in parallel, which is why close coordination between these two groups of activities is needed. At the construction site, costly delays can occur if the manufacturing plant does not provide enough building elements on time. On the other hand, early production of building elements when they are not needed increases the cost of storage. It makes on site material manipulation more complex and seriously affects other projects in a multi-project environment.

In the process analysis we have identified two main areas of improvement which could significantly improve the overall performance. Firstly, an integration of building design and industrialized production should be achieved in a way that prefabrication can directly use up to date building design data for automatic calculation of material quantities. This improves planning and organization of prefabrication processes. Secondly, on-site project management and project documentation related activities should be consolidated and integrated with the manufacturing, which improves efficiency of logistics, on-site material handling and overall project progress tracking. As the first step of improvement, two specific goals have been set on a short term scale: (1) project progress monitoring should be improved with a new system, and (2) tracking of the status of building elements should cover both prefabrication processes and construction site works and become transparent throughout the company.

3. Overview of relevant BIM aspects

Next to industrialized construction, integration and interoperability have for several years been a very important topic in the construction industry in general. Research and development efforts have led the community to product modeling and nD modeling, and finally to building information models. All these efforts have always and repeatedly produced the need for data exchange between tasks, stakeholders or systems. The results of these developments guided us to base our integration efforts on an extensible BIM platform, which will provide the basis for future developments in the company.

As described elsewhere, the building information model (BIM) [6,7] contains information needed in particular phases of a building's life-cycle (scheduling, analyses, cost evaluation, etc.). It is much more than a data container for the building model; it is an object oriented building design. Information structures of the design are presented as objects (walls, columns, windows, doors, etc.) with attributes and relationships between building elements. BIM provides a logical and consistent access to these objects, using a standardized approach such as STEP or IFC. Early ideas were more optimistic in applying a complete BIM for the purpose of the whole building life-cycle. In this regard, feasibility studies and tests were performed to check if existing standards can be applied, like in HUT 600 [8,9]. Efforts were made to extend the usage of building information beyond early design and construction, mostly in search of solutions suitable for maintenance support in projects, such as LifePlan [7,10], DESNET [7,11,12] or ProIT [7,13,14]. Since all product modeling initiatives have not arrived at one common, generic and interoperable data exchange solution, more practical schemes appeared from projects like BLIS [15], which is set towards defining and implementing pragmatic subsets of the IFC model on both software vendor and end user sides of the bridge. Another initiative Ifc-mBomb [16] focuses on the most important bottlenecks in data exchange — data responsibility handover from design through construction to maintenance. In addition to pure data exchange, several projects around the world emphasize reengineering and integration of processes and building life-cycles, among them are SARA [17,18] and CORENET [19–21]. The latest initiatives also include standardisation initiatives such as BuildingSmart [22,23] or the Norwegian initiative [24] which have great influence on the industry via legal demands.

We used this rich body of knowledge in the field of BIM in our efforts to link information from the ERP system with the building design data. BIM is put into the central position of the system. It serves as a platform for the integration of different perspectives implemented in the form of unlinked parts of an existing information system. The model becomes the common denominator which makes the construction process more transparent. Transparency and interoperability reflect construction site activities in the ERP system. It contributes to a better understanding of project boundaries and hence the financial consequences of building design related decisions. Transparency between construction works and manufacturing processes makes short term planning more accurate, which leads to a shorter construction process with reduced delays and a lower demand for material buffering. Similar results were also recognized by other authors [25]. And vice versa, it makes the planning of prefabrication processes more efficient in a multi-project environment.

4. System architecture

Previous experiences with BIM, reported by other authors [26], clearly show that the pragmatic and stepwise approach is more effective when introducing a model based approach into construction. We therefore focused our work on the interconnection of subsystems in the company through a rather simple BIM. At this stage, the model is not the main repository of building information which serves all processes in the building life-cycle. However, open architecture based on the IFC standard provides the basis for future developments in this direction. The overall system architecture is presented in Fig. 1.

Fig. 1 shows the connections between the pre-existing ERP system, CAD tools and the construction site via BIM. In addition to these three main parts we rounded up the architecture with a document management system (DMS) that handles unstructured project information, and a company portal as an infrastructure that improves project communication inside the company and also serves the needs of outside stakeholders.

Overall project planning, pre-sales activities, purchasing, production and logistics are handled by the ERP system. Building elements, either purchased from other suppliers or company-made, are tracked by the ERP until delivered to the construction site. To achieve the goal of tracking the status of building elements through the whole building process, statuses from the construction site should be included as well. Here we faced a problem of granularity, because in production it is sufficient to track the progress status on the level of transport units. At the construction site, however, where tracking of statuses such as "on-site" or "mounted" are important, status information on a transport unit has no real value any more. BIM provides the mapping between the ERP level and the construction site level of granularity. The extension of building element status information to construction site contributes to the transparency of material flow tracking. This opens possibilities to automate material tracking with technologies like RFID and also enables quick visualization of available and needed material at the site.

An analysis of the existing practice showed that in detailed design two different modelers are used, one for modeling the load-bearing construction and one for modeling the roof and façade elements. From these designs, blueprints are prepared and a semi-automated transfer and a partially manual entry of the bill of materials data into the ERP system were performed. The introduction of BIM integrated these two models into one consistent building model. In general, any number of submodels or domain specific model views can be merged into

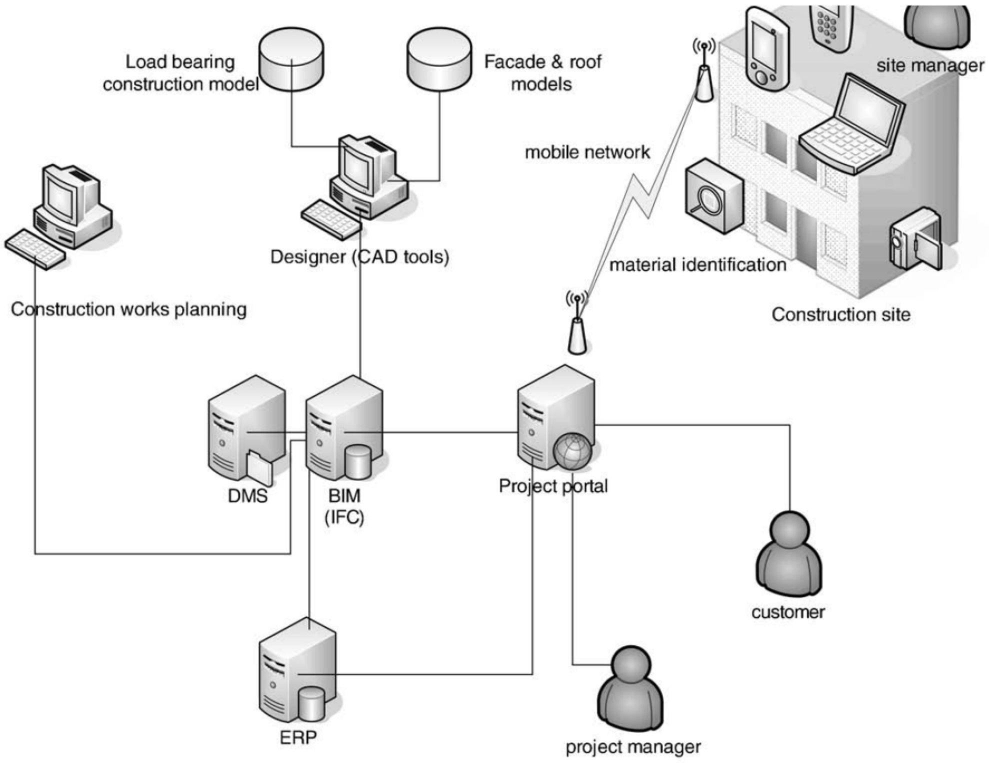

Fig. 1. System architecture.

integrated BIM. The bill of materials is now loaded into the ERP system from the BIM for the purpose of organizing the manufacturing process. Here again we face the above mentioned problem of granularity, since the identity of particular designed building element is not important for prefabrication process. This problem is described in more detail in the following subsection.

To implement BIM, we followed the IAI IFC standard. At the moment, the modelers used at the company do not provide an IFC interface. However, it is reasonable to assume that in the future the situation will improve. For the purpose of our project we developed IFC interfaces for CAD tools and the ERP system in use. It is important to point out that libraries for reading IFC data structures are already available, which is significantly shortening the software development life-cycle. In our efforts we have used TNO's IFC Engine [27] and IFC library developed by Secom IS Laboratory [28]. Initially, the building elements stored in BIM contain information on element geometry. In addition to geometry, the model also contains information needed for tracking the status of the elements and also all data needed for the automated preparation of daily field reports and calculation of quantities of the spent material. In the first step, only the main building elements such as columns, beams and façade plates are stored in BIM. Information about mounting material and minor elements is not stored in the BIM, but is referenced via their transport units into ERP system and linked to the main elements. Building elements are also linked to the activities in the project plan. At the moment, this is not handled by IFC classes, but the project plan is stored in separate file in XML format generated by Microsoft Project. External references between WBS elements of the project plan and building elements are documented by IFC property sets on a level of building element. We should point out that such 4D model can be very detailed, however until higher level of automation in building 4D models is invented our suggestion is to use more coarse models to avoid to put too much workload on the project manager and site manager with regard to detailed planning.

In addition to the structured information about the building object itself, there are lots of unstructured documents in use during the project. In our efforts, we handled this information with the existing tools available at the company. Most of the documents are managed through a project portal which serves as a simplified DMS system.

The presented architecture and information links enable the implementation of functionalities for planning and control of the construction site. At the end of the project information chain, the data on the project progress are collected in daily field reports. Before new tools are put into service, most of the time daily field reports were handled in paper format. The site manager filled in the data by hand, made all the necessary sketches and manually calculated the quantities. The new architecture provides the site manager with a tool that collects information on the recorded project progress and prepares digital sketches. It also calculates the quantities and generates forms for daily field reports, which can later be updated by the site manager with details that cannot be derived from information available in the system. Traceability to the requirements stored in the ERP system provides the financial consequences of the current project status, while the links between building elements and the project plan provide information on the difference between the planned and accomplished work. The same tool is used at the construction site to monitor the availability of building elements and to record the status of construction activities on the 3D model of the building. A wireless network connection is used (GPRS or UMTS) for the exchange of data on building elements at the manufacturing plant and the construction site. Progress information on manufacturing processes and construction site processes is transparently available to all project participants.

4.1. Interoperability between CAD and ERP

In our research we have found that interoperability between CAD and ERP systems and transfer of information in both directions is affected by transfer of building element identity from design through prefabrication to construction site processes. This problem has roots in the very nature of on-site construction processes. Enforcement of traceability on the level of particular building element would generate big organizational and logistic problems, because many building elements are interchangeable. To avoid the problems, it is necessary to separate the identity of designed building element from physical identity of material and/or prefabricated building element.

On the other hand, to achieve traceability and control over material flows it is necessary to establish a link between the above mentioned identities. One possible solution to this problem is the introduction of more abstract element type. Building model defines element types and the type is assigned to particular occurrences of the elements. In this way, all interchangeable building elements are linked. The mapping is established that provides the basis for definition of algorithms, which are necessary for the calculation of material requirements and flows throughout the project. At the same time, this abstraction does not have negative impacts on logistic processes and on-site material handling, because it preserves the ability to swap interchangeable elements. Also the abstraction itself does not affect the model's initial level of detail, which is important for reporting and management of construction site.

5. Construction site application

The first stage in the implementation of the proposed system focuses on project progress monitoring from the construction site perspective, and tracking of the building elements' production and delivery. In previous chapters we described the role of BIM in this context. Two examples described in this chapter illustrate the benefits of ERP and CAD data integration.

In the process of tracking the prefabrication process and material flows to the construction site, both sides of the supply chain are involved. The production unit tracks and updates the status of building elements when they are in production. The information is propagated from the ERP system to BIM and becomes available to the site manager, who uses this information for the detailed planning of construction works. The planning is performed using a 3D model of the building, where the status of elements is evident. He is immediately aware of any missing element for the planned activities. On the other hand, the planned status of the building at a particular moment in time informs the production unit of the construction work dynamics and enables a better organization of production and a proactive material supply.

Project progress monitoring can also be enhanced by the described system. The site manager reports on the accomplished work at the construction site on a regular basis. In model based working, the site manager reports on the performed work by selecting the constructed parts of the building on the 3D model. Building elements can be selected either via spatial selection in 2D or 3D (as shown in Fig. 2) or by using lists of elements and/or different grouping criteria like project activity or part of the building (ex. storey 1, north façade, roof, etc.), Status of work progress is assigned to each particular element. This has deeper implications for further progress reporting.

From the status of building elements, the application can calculate the quantities of spent material and generate 2D projections of the already constructed parts of the building for the purpose of daily field reporting. The project manager, who is usually responsible for several projects and construction sites, gets prompt information on the activities at different locations. He is informed either via getting annotated blueprints and reports in electronic format or by directly connecting to the system where he can explore the model and where status of the building elements is shown in different colours. The project manager can compare as planned and as built situation and also identify existing or forthcoming difficulties related to material production and delivery. On a more abstract level and accompanied with photographs from the site, the customer can be informed on the project progress as well.

Similarly to these two examples, several other tasks can become automated. The site manager can get all the properties and details concerning the building elements. Specific assembly instructions can also be linked to building elements and displayed on site. Since all information is available to both the production unit and construction site, this forms the basis for automated tracking of material flows with technologies, such as RFID, etc.

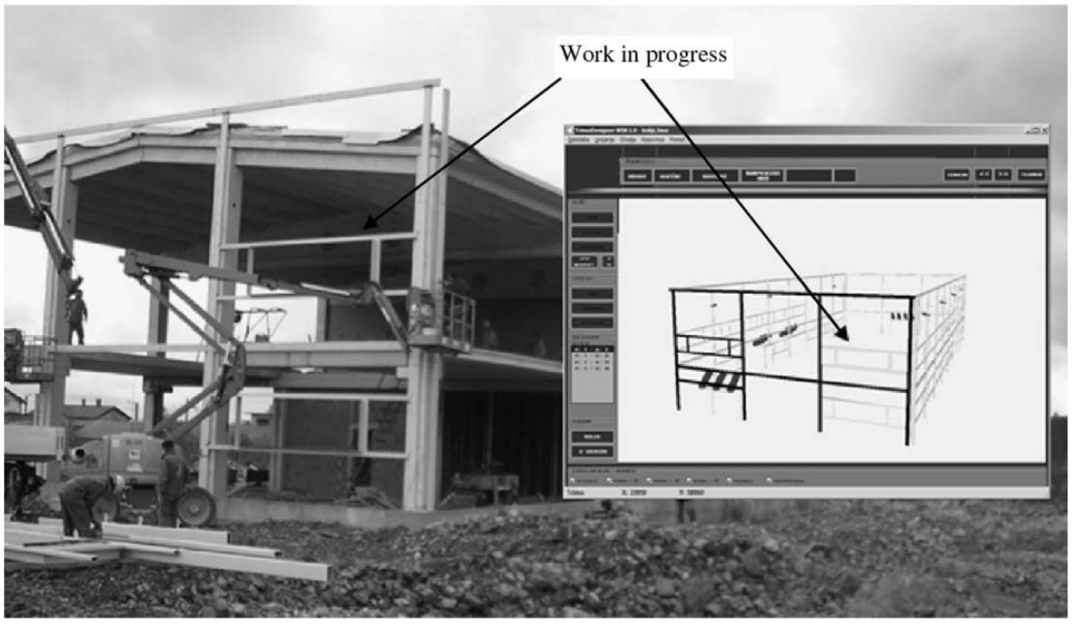

Fig. 2. Reporting of work progress via 3D model.