White Paper

Intelligent Design of Industrial Steel Buildings – a BIM approach

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ABSTRACT: **BIM** or **Building Information Modelling is the evolutionary process of representing one central model within multiple disciplines**. BIM creates and maintains in realtime multi-dimensional, datarich "views" through a project lifecycle to support communication (sharing of data), collaboration (acting on shared data), simulation (using shared data for prediction), optimization (using feedback on shared data to improve the design), documentation and delivery [Ref.1]. This BIM support is currently being implemented in most major design software packages for architecture and engineering. This paper focuses on BIM for Industrial Buildings.

Pre-Engineered Metal Building Systems

The majority of industrial buildings are made out of steel, yet in some countries precast concrete is adopted or even a mixed form of steel and concrete building parts. This paper concentrates on industrial steel buildings, with a focus on pre-engineered metal buildings (PEB). The metal building industry dates back to the early 1900s with the production of small buildings for use of garages, tools sheds and shelters for men and equipment. Later it moved on to build warehouses, aircraft hangars and utilitarian storage buildings. In the 1960's the metal building industry developed further with the boom in agricultural and industrial buildings, leisure in-door halls (tennis), car sales outlets and shopping centers. To reduce the costs, the manufacturers adopted the "pre-engineering" concept, where they choose to design, detail and fabricate a defined group of standard buildings of set widths, heights and loadings. The majority of pre-engineered buildings are chosen from a specific combination, offered by the manufacturer, by varying the span, height, bay size, loading systems and foundations with limited set of choices. From a catalogue of standard parts, the manufacturer quickly interpolates inbetween existing designs to work out a new proposal. By this, metal building systems have evolved through the years into assemblages of structural elements that work together as an efficient structural system. While there are many variations on the theme, the basic elements of the metal building system are constant: primary rigid frames, secondary members (wall girts and roof purlins), cladding and bracing. All major metal building system manufacturers utilize computer tools to custom design a building system and all building components, based on the customer's specifications. Adhering to the local and national building codes, each metal building system is engineered to the required dimensions and designed to meet the loading conditions with the material specified. [Ref.2] There are several software solutions on the market (both commercial and inhouse developed) which generate, in batch mode, the full design and detailing. Today's metal building systems also look much different than their predecessors. Metal buildings are extremely versatile, and can incorporate many different architectural finishes to provide the look required for applications such as churches, schools, shopping centers, office buildings and more. Today clients request a much more customized building, without a real standard. The spans, frame height, bay size as well as all other dimensions do not accept prescribed choices any more. The building geometry proves of architectural freedom to reflect modernism and status of the building owner.
Nevertheless the building components of metal buildings still refer to the real "pre-engineering" past: rigid frames made of high yield tapered steel members, bolted or welded steel connections, cold formed purlins and girts, various types of roof and wall panels, bracing systems… [Ref.2].

The Integrated Engineering Design Process

A PEB is made out of a primary and a secondary structure; the primary structure consists of standard primary steel frames and secondary members purlins, girts, wind bracings and foundations (Figure 1). The secondary model consists of end and side walls, cladding, roof system, canopies, cranes, mezzanines, a.o. The weight of the primary structure is defining a main percentage of the building cost.
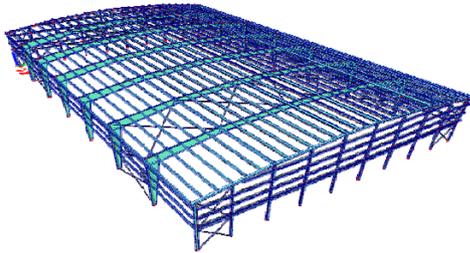

Figure 1. Pre-Engineered Building

The current practice is to use tapered members of built-up steel sections with a varying section height and varying thicknesses of web and flanges (Figure 2). With this technique building spans of over 90 meter have been realized.
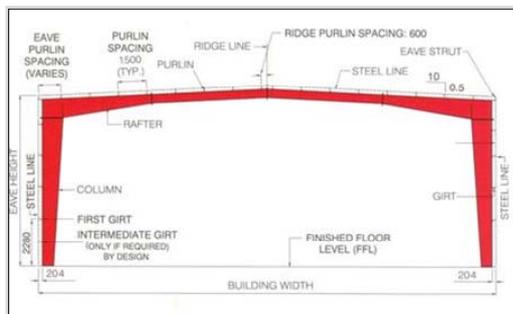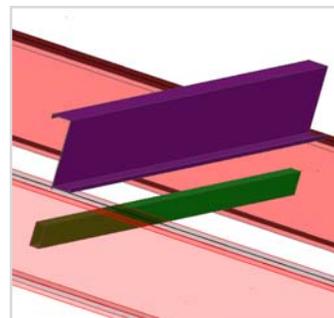

Figure 2. Tapered member frame   *Figure 3. Strut*

Also the purlins are standardized, usually C, Z or Sigma cold-formed sections which can be strengthened with struts (pipes or tubes) (Figure 3). In addition the cold formed purlins can be replaced by joist for larger spans.

The optimization of the many design variables has always been a challenging engineering task. In the past PEB companies tend to calculate thousands of variants of standard building systems, and generate tables to be used by interpolation for new buildings. This gives nor flexibility nor sufficient precision. And in addition, an economical design is not secured.

Recent progress in engineering design methodology has introduced mathematical programming and heuristic algorithms which are extremely fast and efficient in finding a minimum weight solution, starting from or without an initial design, with respect to the practical constraints (maximum beam lengths, available stock, code checks as steel, fire or cold formed design for EC-EN or NAS). An example of the consecutive steps of the optimization is illustrated for one frame (Figure 4).
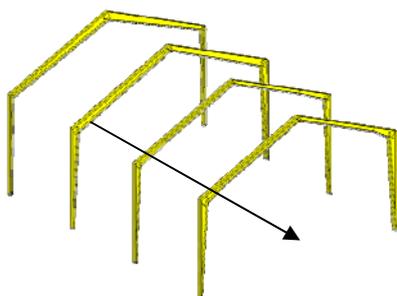

Figure 4. Frame Optimization

The industrialization of PEB is parallel to mass production; however, each project is different from another and requires an individual price estimation by dimensions, utilization and customer choices. The process of price calculation, based on an automated engineering design, illustrates the BIM technology approach. The structural model joins together the technical information (engineering details) as well as commercial or economical information (the cost of elements) in one integrated solution. The user interface of an integrated software solution is adaptable to the user competence level. Trained sales engineers and/or PEB builders/dealers will simply apply engineered company-prepared templates that generate the model including loading, support conditions, etc. With this black box approach the designer still succeeds, from the pre-sales status, in generating an optimized structure, out of which a price proposal is generated.

It is obvious that also the secondary model needs to be defined to have a complete final picture of a project. In several cases the secondary structure will have an important impact on the primary structure, for example the position of bracings could be limited by door and window openings, the purlin and girt design could be influenced by the type of sheeting and so on.

It means that the underlying software system needs full modelling capabilities, to visualize the entire project and to generate a correct bill of material including the accessories (Figure 5).
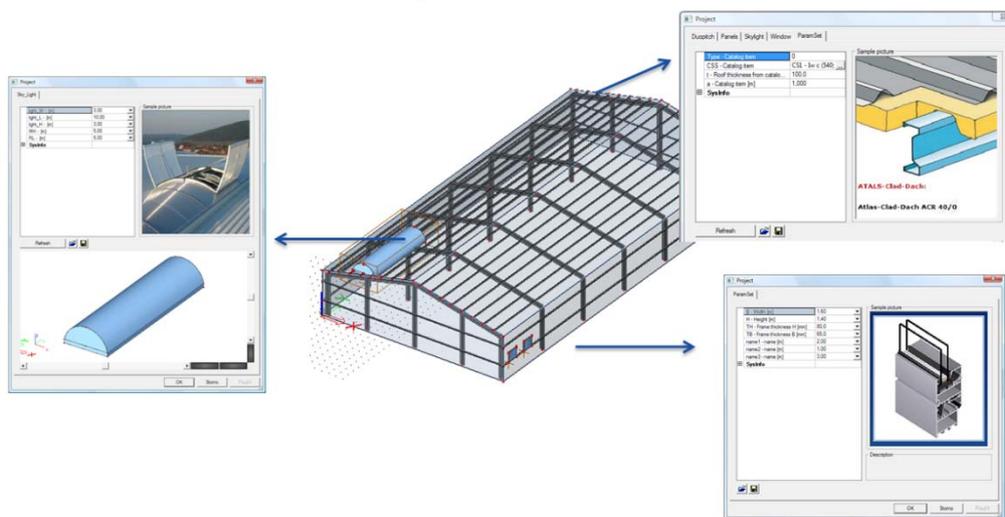

Figure 5. PEB with accessories

This bill of material is the basis for the price estimation. Each PEB company has specific rules to estimate out of the geometry the real costs of materials, production, erection, transportation, etc. The BIM solution covers the full proposal documentation (contract proposal, engineering design, arrangement drawings, details, material lists, and cost details). A direct link to CRM and ERP systems enables to integrate the offering process in the company's operational organization.

Upon receipt of the order, the already prepared pre-design data from above are used to refine the design using the same tools yet with more engineering design freedom and handled by expert structural engineers. After the engineering refinement, the final design data is sent to the fabrication software using standard exchange formats such as Stepsteel or the latest IFC (Industry Foundation Classes) through which the structural object information is shared with product planning software. Fabrication methods are added to the geometrical data to prepare the manufacturing processes of cutting, drilling, welding, etc. of the building parts.

Parametric Structural BIM

In contrast with the currently used batch automation at PEB companies, a novel technology is presented. Parametric 3D modelling , as applied in most mechanical CAD systems, has been implemented in the Scia Engineer CAE platform. The implementation is such that users are able to specify themselves the parameters of the so called In-Blocks (Intelligent object Blocks) in interactive operational mode. All structural members have a property table (with attributes the user may parameterize), a function (e.g. structural) and a graphical representation. In addition all these objects are accessible from outside (via XML).

The innovation is such that In-Blocks have parametrical intelligence: the internal intelligence allows adopting simplifications, to follow code assumptions or to mix levels of finite elements (1D, 2D). An In-Block is equipped with all information for making of specific checks; it provides the specific data for the bill of material or for drawings. In-Blocks can be nested or chained, properties being linked to the ones belonging to In-Blocks of a higher hierarchy through a 'member composer'. Finally by creating templates an administration user gets access to the In-Blocks and can generate or allow generation of models as part of a full structure.

The enduser only has to specify the parameters preset by the application; as an example a full frame is generated in Figure 6.
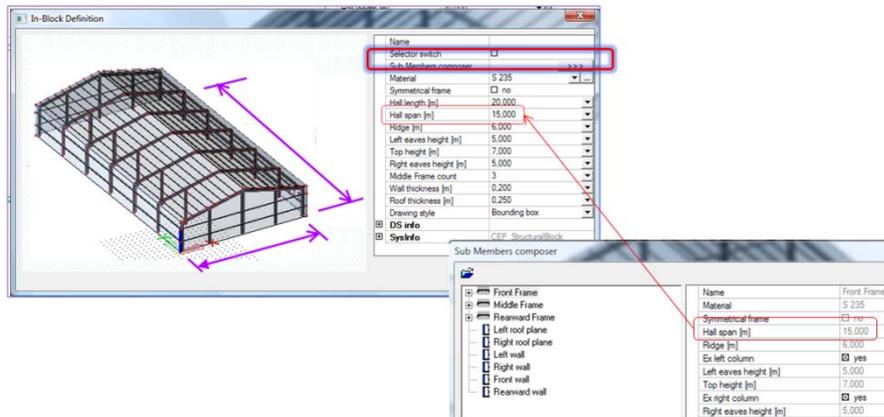

Figure 6. In-Block frame generation

To place an In-Block into a structure, insertion points are used. Insertion points are set in properties or defined graphically by mouse. Each position of a member in the structure is named a 'member instance'.

An In-Block is used in a project more than once – each member definition has more member instances. When editing one, all In-Blocks in the structure are changed. The In-Blocks can be inserted in a matrix with steps, repeated in one or more directions or be positioned more sophisticated along for example curved lines. Different input functionalities can be applied depending on the specific modelling concept at hand.

Another application of In-Blocks concerns connections. A connection object manages basic features, such as the 1D-members which are connected, the collision of those members, the generation of natural inserting points... Each connection is composed of any number of items as plates, stiffeners, ribs, bolts, etc. Each part may be an In-Block. Figure 7 shows a connection of a rafter and purlin. The red part is the nested template, which derived its properties from the Z shape parameters (inverse parameters) and reacts on changes of the cross-section dimensions.
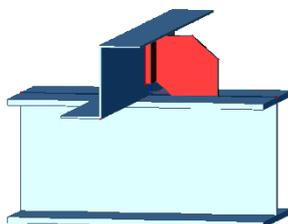

Figure 7. Nested template for purlin-rafter connection

As a general modelling technology is incorporated, there are no practical restrictions for generating any type of industrial building, giving full freedom to the user. It is obvious that two types of users are in view: the 'Super-User' or Administrator, able to configure the application (by setting-up of parametric In-Blocks and templates), and the 'End-User' who fills in the templates.

Geometry and Loadings

Every PEB manufacturer has defined his standards of primary and secondary structure, including the building parts, the materials, and the construction methods. To automate the generation of 3D building geometry, these standards must be added to the modelling software, using the In-Blocks, libraries and templates. Typical examples for a main portal frame definition and a typical door installation are given in Figure 8. The same applies for the loading, be it dead load / live load / wind load / snow load / …. The availability in the standard generic CAE software of generators facilitates the automation for PEB structures. More geometrical issues are addressed by the software: roof and wall openings, wind bracings, crane runway positions, canopies, etc.
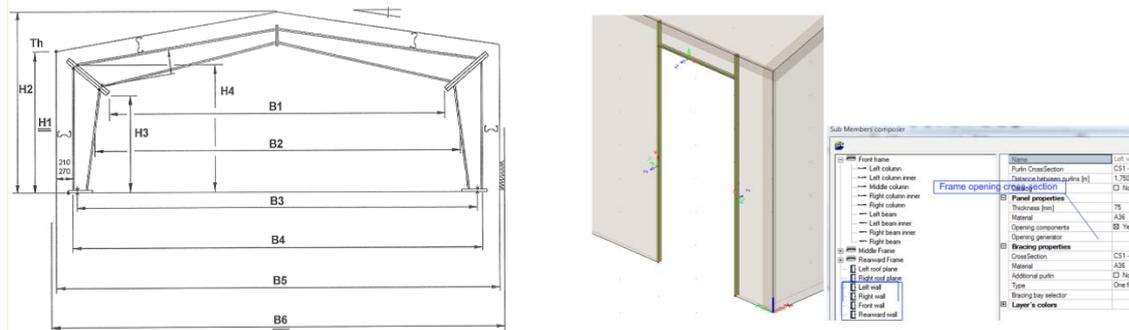

Figure 8. Portal frame definition and door installation

Analysis and Design

An important aspect of a PEB structure is the optimization of the structural members, mainly the steel frames, purlins, girts, wind braces and foundations. Scia has implemented several methodologies, the simplest being the variation of parameters and performing consecutive calculations.

The most advanced concerns a gradient mathematical optimization algorithm [Ref.4]. Since frames in PEB's are made of tapered members, a general approach is applied as follows:
- A frame consists of beams, composed of N parts (prismatic or with variable height).
- Each part ends in a X_i position. Some of the X_i positions can be fixed, some of them can be moved.
- At each X_i position is a height H_i. Here also some of the H_i heights can be fixed.
- The cross-section is an I-section, either symmetrical or nonsymmetrical.
- The thickness of the web is designed separately.
- Each flange has dimensions b_i, t_i, both are constant along one part. In some cases there can be a condition $b_i = b_{ii-1}$. (Figure 9).
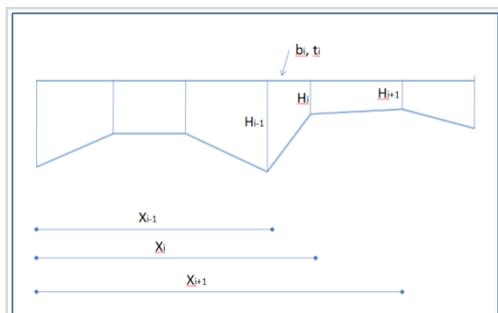

Figure 9. Parametric tapered member model

The gradient method is applied with initial parameters (cross sectional characteristics, materials, member data, buckling data, loads, …), the optimization concerns the length and height of the

haunches, taking into account constraints of all variables (e.g. allowable stresses, maximum deformations). The initial heights are based on simple formulae.

The internal forces are calculated and standard code checking formulae are applied. Then the optimization algorithm starts by adapting the variables, recalculating the structural internal forces and the stress checks till convergence with respect to the goal (possibly the weight) is obtained. In Figure 10 a simple example illustrates the search of the optimal b (width) and h (height) of a clamped cantilever beam (with rectangular section bxh) under a point load at the end.

The graph shows annotations including:

$$\frac{b}{h} > \frac{1}{12}$$

Optimum b = 16mm, h=192 mm

$$\sigma = \frac{6.l.F}{b.h^2} = \frac{6.1000.10^4}{b.h^2} < 100 MPa$$

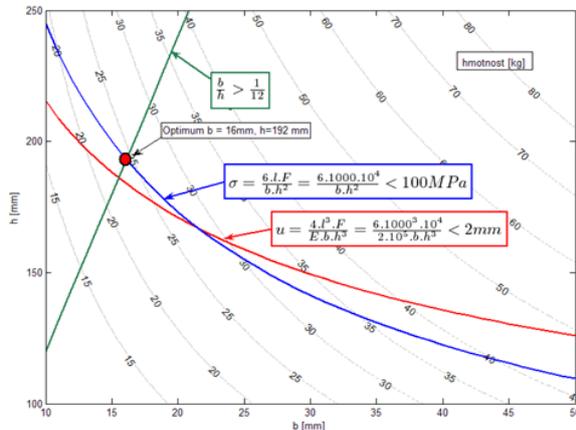$$u = \frac{4.l^3.F}{E.b.h^3} = \frac{6.1000^3.10^4}{2.10^5.b.h^3} < 2mm$$

Figure 10. Gradient method illustration

The design follows prescribed codes for checking the members; the unity checks (combining normal forces, shear forces, bending moments, buckling factors, etc) have been implemented for a variety of codes, which includes IBC (AISC, ASCE, AISI) and the Eurocodes. The code checking is applied for all structural members, foundations, frame members, purlins, wind braces, etc. Depending on the construction method the design rules will deliver an optimal solution.

Document, Drawing and Detail Generation

The more automation is implemented, the more clarifications are required in the documentation of the design. Engineering and calculation reports, code checking proofs, arrangement drawings, structural details … are generated during the design process, either in batch mode or in interactive user driven mode. Samples are displayed in Figure 11-12. For a lively report, full use is made of the 3D PDF (acrobat) representation functions.
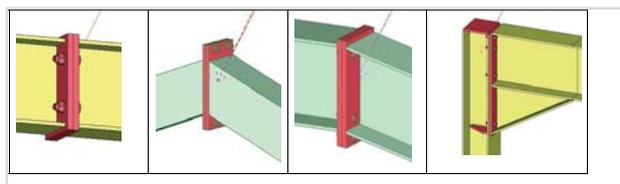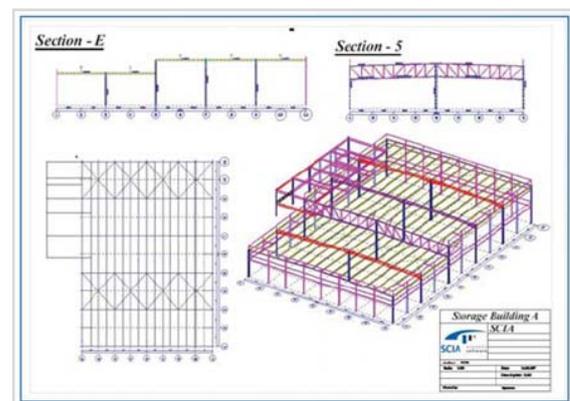

Figure 11. Connection detailing

Figure 12. Overview drawings

SQL Server Implementation Of The BIM Model Via Ifc (Building Information Model)

How important the engineering design may be, finally a project must be agreed, sold, fabricated, erected and delivered. PEB companies are highly competitive; much of their value is situated in the quality of their product and services, in which the speed of design and execution are absolute decisive factors. Part of the value – however – is the pricing, which is related to the companies' industrialization level. A distinguishing factor between companies is their capability of quickly generating an exact price of a project. To support the sales quotation process, Scia has implemented an innovative methodology, using the 3D intelligent building information of the 3D model. To enable the use of the building component properties in a structured way, a direct link was realized between the engineering software and a relational SQL database, using the IFC technology. IFC (Industry Foundation Classes) is an ISO standard for exchanging digital model information in the AEC industry [Ref.7]. Having an IFC level 2x3 certification for data exchange of the structural model, the object information from Scia Engineer is exported to a relational database (an IFC server concept).
By this approach, the model data become manageable for alphanumeric handling. One application is the price quotation where the model data is extended with up-to-date material pricing, the latest surface treatment costs, and company-related fabrication cost estimates, transportation and erection costs. Again company specific rules are implemented in the price calculation method.
By using a standard IFC format more extra benefits are obtained: integration with other software accessing IFC model data (e.g. architectural software, visualization software…), extending the information towards production management, material handling and overall management topics. More benefits of this approach will come.

Summary

This paper focused on the application of BIM (Building Information Modelling) for Industrial Metal Building Systems. The different steps of the integrated engineering and design process are summarized on the following diagram (Figure 13).
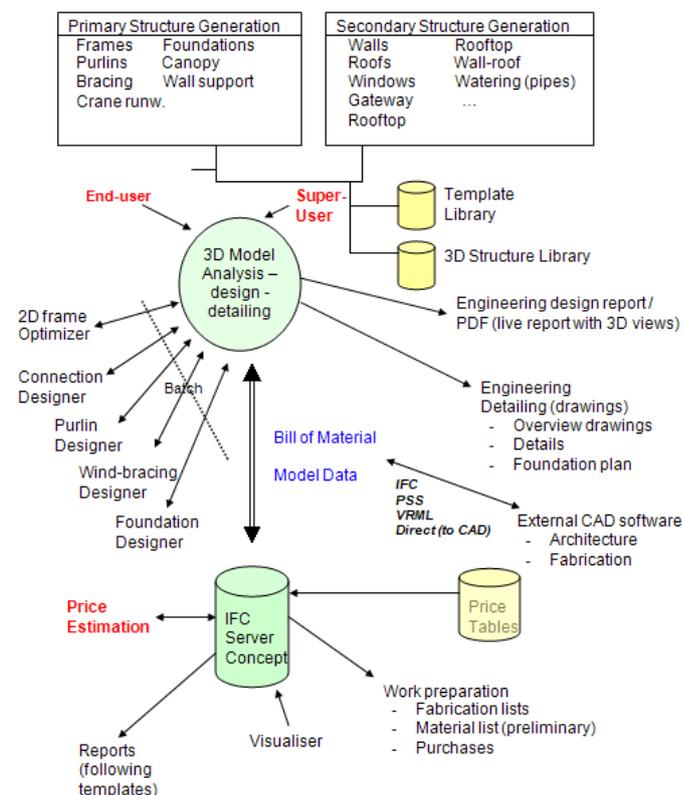
Figure 13. Integrated engineering and design process

A novel technology has been presented based on parametric 3D modelling within the Scia Engineer CAE platform. Using Intelligent object Blocks (In-Blocks) a 'Super-User' is able to generate company templates for any kind of Industrial Building. The In-Blocks include both elements of the primary and the secondary structure in order to provide a complete overview of the project.

The 'End-User' merely needs to fill in the desired parameters of a template in order to generate a full 3D model. This model is used for Analysis, Design and Detailing which includes design of purlins, bracings, foundations ... In addition an advanced 'gradient mathematical optimization algorithm' is applied for optimizing the tapered frames.

From this 3D model, a full Bill of Material, drawings, reports … are generated directly. Through IFC (Industry Foundation Classes) the model is directly linked to a relational SQL database which is used for price estimation, cost calculation, work preparation and so on.

In addition, the model can be exchanged with external CAD software.

The end result of this Parametric Structural B.I.M.is a complete solution for Industrial Engineered Metal Building Systems.

Acknowledgements

References and Literature List

[1]   Building Information Modelling
        http://www.laiserin.com

[2]   Metal Builders Manufacturing Association
        http://www.mbma.com/

[2]   Introduction to Pre Engineered Buildings, Gursharan Singh, 2008
        http://www.engineeringcivil.com/pre-engineered-buildings.html

[3]   Automated Rule-Based Building Design and Engineering at Robertson Ceco Corporation,
        Lachmi Khemlani, 2005
        http://www/aecbytes.com/buildingthefuture/2005/RCCstudy.html

[4]   Practical Mathematical Optimization: An Introduction to Basic Optimization Theory and
        Classical and New Gradient-Based Algorithms. Jan A. Snyman (2005), Springer Publishing.
        ISBN 0-387-24348-8

[5]   Impact of three-dimensional parametric modelling of buildings on productivity in
        structural engineering practice, Rafael Sacks, Ronen Barak (Faculty of Civil and Env.
        Engineering, Technion-Israel Institute of Technology, Israel, August 2007, Elsevier (Science
        Direct)

[6]   White paper on PT Structural Modeler / Scia software for Structural
        Building Information Modelling   (S-BIM), Dr. Jean-Pierre Rammant, CEO of Scia International
        - June 2004
        http://www.scia-online.com

[7]   International Alliance for Interoperability
        http://www.buildingsmart.com/