

THE ASSESSMENT OF CONSTRUCTABILITY: BIM CASES

SUBMITTED: October 2014

REVISED: December 2014

PUBLISHED: January 2015 at <http://www.itcon.org/2015/4>

GUEST EDITORS: Mahdavi A. & Martens B.

Matti K. Tauriainen

*Aalto University, School of Engineering, Department of Civil and Structural Engineering, Espoo, Finland;
matti.tauriainen@aalto.fi*

Jari A. Puttonen, Professor

*Aalto University, School of Engineering, Department of Civil and Structural Engineering, Espoo, Finland;
jari.puttonen@aalto.fi*

Arto J. Saari, Professor

*Aalto University, School of Engineering, Department of Civil and Structural Engineering, Espoo, Finland;
arto.saari@aalto.fi*

SUMMARY: *The constructability appraisal methods developed so far are based on evaluating and analysing the major design components and systems of an entire building, such as structural systems, materials and production techniques. At first, this paper discusses the current practice of constructability assessment used in Finland and next it introduces an experimental constructability assessment method (ECAM) using building information models (BIM) as a source of constructability information. Interviews of design and construction professionals were used to explore the current practice of constructability assessment. An experimental assessment methodology was developed and tested in case projects. According to the interviews, the main assessment method used was the inspection of drawings, and constructability was assessed occasionally during the design development stage and more systematically at the very end of the detailed design stage with varying professional participants in meetings. Using ECAM in the project level a constructability score of a building and building type can be analysed. When using ECAM on the level of structural elements a constructability score of elements can be measured. These scores incorporate information for the development of constructability. In Finland, the development of a systematic review process of constructability will be needed. The constructability assessment methodology suggested in the article is experimental and is to be developed and tested further before using it reliably in building projects. The assessment combining visual and analytical approach will change present methods for assessing constructability.*

KEYWORDS: *assessment, analyses, buildability, constructability, modelling, BIM, quantitative*

REFERENCE: *Matti K. Tauriainen, Jari A. Puttonen, Arto J. Saari (2015). The assessment of constructability: BIM cases. Journal of Information Technology in Construction (ITcon), Special Issue: ECPPM 2014, Vol. 20, pg. 51-67, <http://www.itcon.org/2015/4>*

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1. INTRODUCTION

In Finland, the content of constructability is not well known, and this is one of the first researches on that research area. The objective of the research was to clarify the concept of constructability and how it can be executed, assessed and developed in different stages of construction project and in companies.

According to several international research and development articles good constructability improves construction performance, productivity and quality. The use of building information models (BIM) at the design and construction stages contributes the achievement of the construction objectives of time, cost and quality. BIM simulates the construction project in a virtual environment. It is possible to make constructability adjustments in the model, and practice construction before it is actualised on a building site. There is still only a limited knowledge of the assessment methods of constructability using BIM as an intensifying technology.

The constructability appraisal methods developed so far are based on evaluating and analysing the major design components of an entire building, such as structural systems, materials and production techniques, and the method, based on the information of individual building parts and components, is not available. Also the linking between constructability assessment and the use of BIM in constructability reviews is poorly addressed in the contemporary research articles and papers. The objective of the research was the development of the methods for assessing constructability at the design and construction stages of a project with building information models. Forming constructability to a more explicit and measurable concept quantitative and qualitative assessment methods that can be applied systematically will be needed. The first objective, a BIM-based tool for calculating a numeric value for constructability, the constructability score, was developed. At the project level, the improvement of constructability can be estimated and developed by combining the visual inspection of BIMs and the constructability score. The need for enhancing the co-operation between designers and site practitioners during early development and design stages was also recognized.

2. RESEARCH QUESTIONS AND METHODS

The research questions were:

1. How did designers, contractor's site and line managers and engineered-to-order producers assess constructability?
2. How could the constructability be assessed using a building information model as a source of information and an analysis tool?

The research started with the literary survey about the methods used previously for the assessment of constructability. At the same time interview themes and questions were developed around the first research question. The interviews were carried out by the research team. At the total of 45 experts from the construction industry were interviewed, such as architects (5) structural designers (10), building services designers (5), building contractor's site and line managers (15), building service contractor's site and line managers (5), engineered-to-order and building material producers (2), and other building industry professionals and researchers (3). Theme, semi-structured and structured interview methods were used. Seven building contractor's and five building service contractor's site and line managers were interviewed using the method of theme interviews or non-directive interviews. The format of interview was such that the respondents were allowed to talk freely around the subject. Structural designers, the other contractor's line and site managers, and engineered-to-order and building material producers were interviewed using semi-structured interviews. The interviewer had a list of questions to be covered, but might not be asking all of them in interviews. The semi-structured interview allows for the probing of views and opinions where it is desirable for respondents to expand on their answers. For architect and building services designers the method of structured interview were used. The interviews were taped and results were analysed.

In the second research stage, the pre-evaluation of the usability of BIM in an assessment of constructability was carried out in three case projects. At the same time previous research about building information modelling and the applications of BIM were also examined. The aim was to examine how constructability could be assessed from the models. (Tauriainen et al. 2012).

Based on the results of the pre-evaluation the first version of an experimental constructability key criterion, constructability factors and the prototype of constructability assessment model were developed. Then suitable building element information was taken off from models and calculations were done using Excel sheets. Simulation rounds with several combinations of factors and mathematical equations were carried out to get an insight in the assessment method and calculation results. Sensitivity analysis of calculation model was carried out. After simulation rounds constructability scores were calculated in cases.

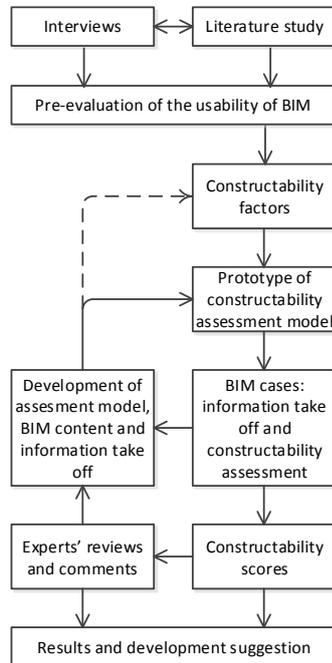


FIG. 1: Research method

At last, constructability scores of four residential buildings and three commercial centre projects were calculated and analysed using structural engineering BIMs as the source of information. The information content of BIMs corresponded to the typical level of detailed design in Finland. The calculation method was also tested using architectural BIM at early design development stage. Visual inspection was tested in one case project. After that, interviews with experts were carried out to get an insight in the validity and relevancy of the assessment method and constructability scores. Opinion of the experts supported the results and findings published in this article.

3. RELEVANT LITTERATURE

In preliminary design Fischer and Tatum (1997) categorized constructability knowledge in three types of design decisions: completing horizontal and vertical layout, and dimensioning structural elements. Critical design variables that are important for the constructability of a structure were the dimensions of elements (e.g. height, depth, width, thickness and length), distances between elements (e.g. clear spans and storey heights), changes in dimensions and distances (e.g. from floor to floor), quantity and type of reinforcements, concrete strength, the repetition of dimensions and distances, and the modularity of layout.

During the first decade of 2000's in Hong Kong, several researches of constructability were conducted (Wong et al. 2006; Lam et al. 2006; Lam et al. 2007, Lam and Wong 2009). The basic idea was the development of Buildability Assessment Model (BAM). BAM is used to assess buildability through scoring different design attributes, e.g. construction systems, building features and site-specific factors. The attributes were identified from the literature to form criteria for a design appraisal system. 63 buildability attributes were developed and grouped under 16 factors. Nine factors related to the design process, and seven factors related to the design output. Based on the feedback for the need of buildability assessment at an early stage of design rather than at the stage when the design is almost complete, the Scheme Design Buildability Assessment Model (SDBAM) was developed. The assessment model and key factors used based on the factors of BAM. It would be used at the schematic design stage. (Lam et al. 2012).

In Canada Alkass et al. (2009) introduced a quantified assessment method for measuring the level of application of constructability principles to building design using 4D/BIM models. In this study 18 different design relevant constructability attributes were identified and distributed to six main groups. These groups constituted the main factors affecting constructability of building design. The groups of constructability factors were named as standardization; economic impact; installation; space; utility availability; and site impacts. Each constructability factors were linked to its corresponding 4D/BIM component in order to evaluate the whole model. According to the research, the best way to test constructability was to simulate the construction of the building and visualize what might go wrong in the coming stages of construction. The BIM-based methodology allowed a 3D simulation of the building and its components, virtual construction before construction began on site, and sharing construction experience between contractors and designers to minimize problems in the construction stage.

According to the Finnish Common BIM Requirements 2012 Series 5: Structural Design, the content of the typical structural BIM at the detailed design stage includes:

- Foundations (piles, footings, foundation walls and columns, and base beams).
- Other substructure elements (slabs, canal structures, special ground floors).
- Structural frame (shelters, load-bearing walls, columns, beams, intermediate floors, ceilings, grid frames and trusses).
- Facades (exterior walls).

The content and accuracy of embedded parts, reinforcements, jointing and other installation parts, the geometry of holes and penetrations varies according to design stages, being the most accurate at detailed design stage.

All load-bearing structures and non-bearing concrete structures are modelled in compliance with the agreed project coordinates. Structures must be modelled such that the location, the name and type, geometry, material, and the content of structure will be expressed and represented. The structural designer defines the structural types of elements and publishes them as drawings. Structures are modelled on the floor and sections according to the planned construction order. Structures that pass through several floors are attached to the lowest floor on which they appear. An automatic GUID numbering is used. In addition, structures are labelled and numbered logically as agreed in the project.

4. ASSESSMENT OF CONSTRUCTABILITY ACCORDING TO THE INTERVIEWS

In Finland, there is not any legislation, a public specification or an instruction for the assessment of constructability as for the example in Hong Kong, Singapore or the United States.

According to the interviews, the assessment of constructability is not very consciously made at the moment by architects. The assessment is made with the methods of quality assurance and co-operation with other project parties, such as client consultants, designers, contractors and material providers. In the schematic design stage, the assessment of constructability, for example the assessment of the multi-formity of the envelope of the building or reservations of the spaces of building services systems is based on the professional skill and experience of the architect. In the building permit stage special attention were paid to the fact that the building meets requirements set in the building legislation. Later on in the design development stages other parties involve in the review process and the assessment is focused on details between and within building system specific areas. According to the interviews, the assessment of constructability is technically carried out using 2D drawings and integrated BIMs as a visual tool.

In the building services design company, the constructability of building service systems will be first assessed within the designer's team, and after that together with other designers in the group of the architect and structural engineer. In later stages, the constructability may be assessed with the client and the contractor. The interviewed mentioned that the meetings and review process should be more efficient, more fluent, and a natural part of the design and construction process. Depending on the client, drawings or building information models are used in the assessment. Design companies may have special schedules for the assessment and inspection. According to the interviews, the assessment of constructability should lie more on the responsibility of the team of building service design. However, this would require more expertise of contracting and assembly of systems from the team at the design stage than nowadays. A general opinion was that the assessment of the constructability takes place immediately at the beginning of the design stage, preferably at the schematic stage. As assessment methods

to be used at the moment were mentioned checking the space reservation of systems, clash checking the objects in the models, and controlling the schedule of assemblies and serviceability of systems.

Among structural engineers the existing method used for assessing constructability was the visual review and inspection of drawings. However, at the same time building information modelling is replacing the use of 2D CAD applications in structural design. The correctness of drawings, sections and main details was inspected including materials, the dimensioning of elements, reinforcements and jointing parts. Structural engineers did not bring especially out such modelling or design stages in the interviews when the assessment of constructability was carried out consciously. They experienced that there is not any special need to carry out the assessment of the constructability as a separate part of the designing stage.

Assessing constructability, site and line managers especially those employed by the principal contractor paid special attention to the control of drawings and building information models. At the detailed design stage, the site and line managers assess constructability visually combining drawing and model information. The constructability of a structural frame is assessed using native file type structural BIM, IFC-file type HVAC/MEP models are used assessing the constructability of building services systems. Also specialized production models based on structural BIM are used for analysing and simulating work schedules, site logistics and construction safety. In general, the site management emphasized the significance of the cooperation between designers, contractors and engineered-to-order (ETO) producers carrying out an efficient design and construction process. The assessment of constructability is a continuous dialogue with the designers, especially with structural designers. Site and line managers felt that the site management can influence the design solutions already at the schematic design stage in the very first design or modelling meetings, but in reality this did not take place in the projects.

In Finland, the detailed design of ETO products, like prefabricated concrete elements, is typically excluded from the main structural design contracts. In this instance, the structural design is the responsibility of ETO producer and structural design work is outsourced to an engineering company. Designing work is carried out in the late detailed design stage during a very tight time schedule, so the ETO producer has only a limited influence to design solutions and constructability.

5. EXPERIMENTAL CONSTRUCTABILITY ASSESSMENT METHODOLOGY (ECAM)

5.1 Constructability factors (CF)

5.1.1 Usability of BIM in an assessment of constructability, pre-evaluation

To get a better overview of the usability of the BIM in the assessment of constructability, the pre-evaluation of the usability of models and the assessment of constructability were carried out in three case projects. Detailed design stage structural building information models were used. The projects were a typical apartment building of prefabricated concrete elements, and commercial buildings of prefabricated concrete elements and of mixed structural systems of steel frames and prefabricated concrete elements.

Several building element types were analysed visually and using the reporting function of the software. Element types included footings, external wall sandwiches, internal in situ and prefabricated structural wall panels, prefabricated concrete columns and beams, hollow core slabs, in situ concrete walls and slabs, steel trusses and assemblies. In the tables and reports the properties of the building elements were, among others, examined according to their naming and identifications, weight, the geometric measures, cross sections and profiles, level of heights and different material qualifications. Different kinds of filters were developed for selecting elements in views and for reporting. (Tauriainen et al. 2012). The results of pre-evaluation were important pieces of input information for developing constructability indicators and the prototype of the assessment method.

5.1.2 Fluctuation of foundation, footing, ground and intermediate floor levels (CF1)

The subsoil conditions have an effect on the design solutions and construction methods of building foundations. When the number of the foundation types increases, civil works will become more complicated and the constructability will be suffering. The subsoil conditions may require more than one foundation type but it was observed that having more than three different foundation types reduces constructability.

The fluctuation in the levels of the foundation bed and footings increases the risks of design errors and errors in excavation and filling works. Minor fluctuation between levels of adjacent footings should be avoided and the difference between levels should not be less than 200 mm.

The differences between intermediate floor levels could be a consequence of different floor-to-floor height and different structural height of floor types. On the bottom level of floor slab even a small difference causes the structural discontinuities with changes in building methods. The elimination of the fluctuation of floor heights and different floor-to-floor heights decreases design errors in the vertical direction, the number of different wall and column types, and systemizes formwork.

5.1.3 Standardization and prefabrication of elements (CF2)

The standardization is done based on norm codes, systemizing product attributes and means of production. The standard solution can be a jointing component, a cross section of a beam, a door frame or a prefabricated space element like a bath room. The standardization intensifies the building process. In the design of (structural) elements and systems based on standardization, simple and repeated design solutions, geometry and dimensionality should be used. The standard design solutions and the recurrence of elements intensify both the design and fabrication of elements and construction work. The number of types of in situ and prefabricated elements has to be kept as small as possible. Simple and repeated cross section profiles and structure types reduce time used for detail design and improve the production rate. The modular dimensionality of elements should be used as much as possible.

Prefabrication of elements reduces construction work and errors on site. Building elements are manufactured at factories, where the production environment is stable and better controllable than on site. Time savings could be achieved in construction work. The principles of just in time production could be applied to construction work. When prefabricated elements are used important properties from the constructability viewpoint will be the use of standardized cross section profiles, minimization of the number of different profile types, and the following of the weight, length, hole and penetrations restrictions of prefabricated elements.

For assessing the constructability of prefabricated elements it is important that all attachments are included. Such attachments are among others temporary supports for transportation, jointing reinforcements and grouting anchors and ties, connecting plates, lifting inserts and lugs, and anchors for temporary studs and safety equipment. Attachments are needed for the transportation of elements and for a safe assembly on site. If critical attachment parts are missing, a prefabricated element could not be used on site and the progress of assembly work is disturbed.

5.1.4 The geometry and dimensionality of elements (CF3)

The length, width, height and weight of element are important constructability factors. Elements with exceptional dimensions (short, long or heavy) should be especially taken care in transportation, site logistics and assembly work. The assembly order, transportation order and loading order of the truck must plan simultaneously. The number of the lifting of prefabricated elements will increase when short elements are used. The weight of prefabricated elements should be around 100 to 200 kN. The weight affects constructability disadvantageously if it exceeds 200 kN.

5.1.5 Reinforcements in elements (CF4)

In the design of reinforced concrete work, a special attention should be paid to the workability of the chosen reinforcement in the structures, especially, when the building element has been heavily reinforced. The density (relative reinforcement quantity) and placing of the main reinforcements, reinforcing order and recurrence of reinforcement elements, and concrete workability are important factors to be considered assessing constructability of structures. The dense steel bar mountings should be avoided in order to facilitate the compaction work of cast concrete. From the constructability point of view the designer should favour reinforcement bars with large diameters instead of smaller bars whenever it is possible. When the diameter of a reinforcement bar is larger than 16 mm, a prefabricated reinforcement element should be used. Mesh reinforcements and fabricated reinforcement spacers should be used instead of bar mountings and in-situ built spacers. So the reinforcing work could be minimized and standardized. Reinforcements in joints should be designed in detail before the assembly of bars or wires begin.

5.1.6 Formwork for concrete elements (CF5)

The formwork of in situ concrete elements should be designed according to the production rate of pouring and concrete works. Prefabricated concrete forms should be used if possible. The number and rate of moulds should be analysed according to the time of concrete stripping. The period of the stocking of moulds on site has to be kept as short as possible.

5.1.7 Holes, slots and penetrations (CF6)

Different types of holes and slots for MEP penetrations and jointing reinforcements is needed in (prefabricated) frame structures and they increase manufacturing cost in the factory or construction cost on site. Also the temporary assembly studs needed must be taken care of. So the number of holes and slots should be minimized, and separate holes should be connected as a larger hole if the better constructability is achieved. ETO producers' size and location recommendation of holes within the element must be followed both in the design and construction of structures.

5.2 Characteristics of building elements in the structural BIM

5.2.1 Frame types

Building frame type refers to the wholeness formed by the load-bearing structures and materials. Horizontal and vertical design grids are developed in the connection to load-bearing structures used in the building. In Finland, typical frame types in the block of flats projects are cross-wall and wall frame unit structures, in commercial and office buildings column and beam frames (both concrete and steel) are frequently used. The frames can be in-situ structures or prefabricated elements. In a building different frame types can be used, for example on the ground floor wall-frame structure and on upper floors a column and beam structures, including different production methods and materials. The use of several frame types in the building leads to several building methods and joint types between the structures which can cause constructability problems, for example the joints between in situ concrete structures and prefabricated structures. Frame types can vary according to the purpose of the use of the building and space requirements, and so the variation can be necessary and thus accepted from the point of view of constructability. In the structural BIM, the frame type is modelled as building elements and could be analysed visually as a whole and quantitatively according to the building element types.

5.2.2 Major structural building elements (sub- and superstructure)

Piling, pad and strip footings are typically modelled in the structural BIM. Types, numbers and dimensionality of elements, building material and vertical and horizontal location of structures can be analysed both quantitatively and visually. In the detailed design stage the reinforcements, holes and penetrations are also modelled.

Column and beams are typically modelled in structural BIM. In an early design stage the dimensionality of columns and beams could only be on a normative base in the structural BIM, but the dimensionality can be analysed statistically using minimum, maximum, average, and variation of values giving the idea of the constructability issues of structures. In the early detailed design stage all attachment parts and reinforcements are included in the building information model and can be reported but visual inspection is needed when analysing constructability.

Intermediate floor and roof slabs are also modelled in an early stage BIM. Types, numbers and dimensionality of elements, building material and vertical level of structures can be analysed both quantitatively and visually. In the detailed design stage the reinforcements, holes and penetrations are also modelled. The number, dimensionality and location of holes and connections to slabs (BIM objects) can be quantifiable if the holes are named properly, otherwise holes should be visually inspected. The important viewpoint of constructability issues is the rate of compatibility of holes with building service system penetrations through structural elements.

Load-bearing walls or wall panels are typically modelled according to the basic geometry and dimensionality of walls in an early design stage BIM. Later in the design stage the dimensionality is designed and modelled according to the requirements of stability, load bearing capacity, functionality and safety of structures. The major hole reservation objects are also included in the wall objects. Types, numbers and dimensionality of elements, building material and vertical and horizontal location of structures can be analysed both quantitatively and

visually. In the detailed design stage the reinforcements, holes and penetrations, and other attachment elements are also modelled exactly.

In the early design stage trusses and gird frames are modelled in their geometrical locations, but the dimensionality rests only on a normative base. The dimensionality of ties, struts, braces and connection joints (structural parts of grid frames) are designed later in the design stage. Grid frame parts are joined together as assembly parts. In the viewpoint of constructability, it is extremely important to analyse at least visually basic dimensions of assembly parts in the connection of lifting and transferring capacity and limitations.

5.2.3 Joints and connection parts

Jointing methods (bolted, welded, pressed, nailed, injected, cast, clued etc.) used for different building materials, elements, and connection parts varies according to the joint types. Working tolerances must be sufficient for jointing methods. Joint types have to be simplified and standardized so that they can be produced easily as well at the factory as on site according to the frame types and the main construction methods used in the building project. The joint types which are familiar to the contractors and ETO producers intensify the production rate and reduce construction defects improving the constructability of the structural frame. Typically, joints are analysed visually, because the information of jointing method is expressed in the detail drawings and specifications.

5.3 Assessment method based on building elements in structural BIM

The proposed experimental assessment method is based on the integration of constructability factors and the main elements of the structural building information model. Design-relevant constructability factors (CF) were identified and formed on the basis of earlier studies (Alkass et al. 2009, Lam et al. 2012) and interviews (Tauriainen et al. 2012 and 2014). Analytic Hierarchy Process (AHP) technique (Saaty 2008, Lam et al. 2007) was used to weight the relevance of the ratings of constructability factors (W_c) and the importance of building elements (W_e). The key ratings of the constructability scores of elements (C_e) are calculated according to the

$$C_e = 1 - \sum(R * W_c) \quad (1)$$

Equation 1.

where R = the rating of the constructability factor; and W_c = weight index of the constructability factor.

Constructability score (CS) is calculated by summing up the weighted key ratings of constructability scores of elements (C_e) according to the Equation 2.

$$CS = \sum(C_e * W_e) * 100 \quad (2)$$

where C_e = the key rating of the constructability score of the element; and W_e = the weight index of the element. The best constructability score is 100 and the weakest is 0.

The calculation method and ratings of constructability factors (R) differ between elements (see Table 2), and the ratings are normalized between values 0 to 1 as presented in the Table 1. The element based calculation methods and ratings of constructability factors are introduced in Equations 3 to 15.

TABLE 1: The normalized rating of constructability factors

Effect on the constructability	Normalized rating of constructability factor, R	$R_{1prof}; R_{2prof}; R_{weight}$	V_{length}	R_{ext}	R_{type}
Very good	0	< 0,01	< 0,20	< 0,05	< 0,005
Good	0,25	< 0,025	< 0,50	< 0,10	< 0,01
Moderate	0,50	< 0,05	< 0,80	< 0,15	< 0,02
Malign	0,75	< 0,10	< 1,10	< 0,20	< 0,40
Extremely malign	1	$\geq 0,10$	$\geq 1,10$	$\geq 0,20$	$\geq 0,40$

The ratings of the constructability factor for section types R_{1prof} and R_{2prof} is presented in Equations 3 and 4:

$$R_{1prof} = \begin{cases} 0 & , q_{prof} = 1 \\ \frac{q_{prof}}{q_{tot}} & , q_{prof} > 1 \end{cases} \quad (3)$$

$$R_{2prof} = \begin{cases} 0 & , q_{prof} = 1 \\ \frac{q_{prof}}{l_{tot}} & , q_{prof} > 1 \end{cases} \quad (4)$$

where q_{prof} is the number of different section profiles, q_{tot} is the total number, and l_{tot} is the total length of elements in question.

The rating of the constructability factor for the number of horizontal levels R_{level} is presented in the Equation 5:

$$R_{level} = \begin{cases} 0, & q_{level} = 0 \\ 0.25, & 0 < q_{level} \leq 3 \\ 0.5, & 3 < q_{level} \leq 6 \\ 0.75, & 6 < q_{level} \leq 9 \\ 1.0, & 9 < q_{level} \end{cases} \quad (5)$$

where q_{level} is the number of different horizontal levels that worsen the constructability of adjacent elements.

The rating of constructability factor of different element types R_{tech} is according to the Equation 6:

$$R_{tech} = \begin{cases} 0, & q_{tech} \leq 3 \\ 0.5, & 3 < q_{tech} \leq 6 \\ 1.0, & q_{tech} > 6 \end{cases} \quad (6)$$

where q_{tech} is the number of element types.

The rating of constructability factor of element weight R_{weight} is according to the Equation 7 as follows:

$$R_{weight} = \begin{cases} 1, & m_{max} > m_{limit} \\ 0, & m_{max} \leq m_{limit} \end{cases} \quad (7)$$

where m_{max} is the heaviest element in question and m_{limit} is the upper limit of the weight for cranes and other lifting equipments.

R_{height} , the rating of constructability factor of element height is calculated according to the Equation 8:

$$R_{height} = \begin{cases} 1, & h_{max} > h_{limit} \\ 0, & h_{max} \leq h_{limit} \end{cases} \quad (8)$$

where h_{max} is the highest element and h_{limit} is the upper limit of the height of the element in question.

R_{type} , the rating of constructability factor for wall types, is presented in the Equation 9:

where q_{type} is the number of wall section types and l_{wall} is the total length of all wall types.

$$R_{type} = \frac{q_{type}}{l_{wall}} \quad (9)$$

The effect of holes, slot and penetrations to the rating of constructability factor of structural frame element is expressed in Equation 10:

$$R_{hole} = \frac{q_{hole}}{q_{hcs}} \quad (10)$$

where q_{hole} is the number of holes and q_{hcs} is the gross area of the element in question.

$R_{holearea}$, the rating of constructability factor for holes that need special infilling (e.g. concrete pouring, insulation), formwork and temporary supports, is calculated according to the Equation 11:

$$R_{holearea} = \frac{q_{holearea}}{q_{hcs}} \quad (11)$$

where $q_{holearea}$ is the area of holes and q_{hcs} is the gross area of the element in question.

The rating of constructability factor of element length, R_{length} , is expressed in Equations 12, 13 and 14:

where l_{max} is the longest or tallest element and l_{limit} is the upper limit of the length of the element in question.

$$R_{length} = \begin{cases} 1 & , l_{max} > l_{limit} \\ \frac{V_{length.n} + R_{ext.n}}{2} & , l_{max} \leq l_{limit} \end{cases} \quad (12)$$

In the Equation 12 $V_{length.n}$ is the normalized value of V_{length} that is the variation coefficient of length of elements.

V_{length} is expressed in the Equation 13:

$$V_{length} = \frac{s_{length}}{\bar{x}_{length}} \quad (13)$$

where s_{length} is the standard deviation and \bar{x}_{length} is the average value of the length of elements. In the Equation 12 $R_{ext.n}$ is the normalized value of R_{ext} . R_{ext} is calculated in Equation 14:

$$R_{ext} = \frac{n_{extlength}}{n_{totlength}} \quad (14)$$

where $n_{extlength}$ is the number of exceptional lengths of elements and $n_{totlength}$ is the total number of elements in question. The length of the element $x_{ilength}$ that is exceptional is expressed in Equation 15:

$$x_{ilength} = \text{exceptional} \quad \text{if } \left\{ \begin{array}{l} \leq 2,5 \text{ m, or} \\ \leq (\bar{x}_{length} - s_{length}), \text{ or} \\ \geq (\bar{x}_{length} + s_{length}) \\ \text{and} \\ \frac{n_{extlength}}{n_{totlength}} \leq 5\% \end{array} \right. \quad (15)$$

TABLE 2: Constructability factors (CF), assessment methods, building elements used in the assessment and rating of constructability factors (R)

Building element Constructability factors	Structural frame system	Structural frame system										Envelope structures				Partition walls				
		Foundations		Beams		Columns		Slabs		Trusses, 3D grid frames		Joints		External walls		Roofs		Load-bearing walls		Light-weight walls
CF1 Number of levels	o/v	o/q/v	R_{level}					o/q/v	R_{level}							c/q/v				
CF2 Standardization and prefabrication	o/v	o/q		o/q		o/q		o/q		o/q/v		o/v		o/q/v		c/q/v		o/q/v		c/q
Prefabrication ratio		c/q		c/q		c/q		c/q		c/q		c/q		c/q		c/q		c/q		c/q
Number of element types		o/q	R_{tech}	c/q		c/q		c/q		o/q		c/q	R_{tech}	o/q/v	R_{type}	c/q/v		o/q/v	R_{type}	c/q
Number of section types		c/q	R_{1prof}, R_{2prof}	o/q	R_{1prof}	o/q	R_{1prof}	o/q	R_{1prof}	c/v	R_{1prof}	o/v	R_{1prof}	c/q				o/q		c/q
CF3 Dimensions of elements	o/v	c/v		o/q		o/q		o/q		o/q/v		o/v		o/q		c/q/v		o/q		c/q
Length				o/q	R_{length}	o/q	R_{length}	o/q	R_{length}		R_{length}			o/q	R_{length}			o/q	R_{length}	
Width				o/q		o/q		o/q												
Hight																				
Weight					R_{weight}		R_{weight}		R_{weight}		R_{weight}				R_{weight}				R_{weight}	
CF4 Reinforcements in elements	c/v	c/q/v		c/q/v		c/q/v		c/q/v				c/v		c/q/v				c/q/v		
Prefabrication ratio																				
Relative reinforcement quantity																				
CF5 Formwork for elements	c/v	c/q/v		c/q/v		c/q/v		c/q/v				c/v		c/q/v				c/q/v		c/v
CF6 Holes in elements	o/v			o/q/v		o/q/v		o/q/v						c/q/v		c/v		o/q/v		c/v
Area of holes				o/q/v	$R_{holearea}$	o/q/v	$R_{holearea}$	o/q/v	$R_{holearea}$					c/q/v	$R_{holearea}$			o/q/v	$R_{holearea}$	
Number of holes				o/q/v	R_{hole}	o/q/v	R_{hole}	o/q/v	R_{hole}					c/q/v	R_{hole}			o/q/v	R_{hole}	

Type of analysis: o = obligatory; c = conceivable; /q = quantitative analysis, measurable; /v = visual and/or qualitative analysis

TABLE 3: Constructability scores (CS) and the key rating of constructability scores of elements (C_e) in BIM cases

Cases	Building element	Structural frame system, Constructability Score CS	Structural frame system										Envelope structures				Partition walls										
			Foundations		Beams		Columns		Slabs		Trusses, 3D grid frames		Joints		External walls		Roofs		Load-bearing walls		Light-weight walls						
			C_e	W_e	C_e	W_e	C_e	W_e	C_e	W_e	C_e	W_e	C_e	W_e	C_e	W_e	C_e	W_e	C_e	W_e	C_e	W_e					
Case 1: Commercial building	c/v	60,3	o/q/v	0,48	0,17	o/q/v	0,45	0,17	o/q/v	0,66	0,17	o/q/v	0,80	0,17			c/v		o/q/v	0,60	0,17						
Case 2: Commercial building	c/v	64,3	o/q/v	0,67	0,17	o/q/v	0,65	0,17	o/q/v	0,77	0,17	o/q/v	0,80	0,17	c/q/v	0,25	0,17	c/v		o/q/v	0,72	0,17					
Case 3: Commercial building	c/v	57,4	o/q/v	0,51	0,20	o/q/v	0,40	0,20	o/q/v	0,38	0,20	o/q/v	0,94	0,20			c/v		o/q/v	0,64	0,20						
Case 4: Residential building	c/v	76,6	o/q/v	0,89	0,20				o/q/v	0,71	0,20	o/q/v	0,86	0,20			c/v		o/q/v	0,70	0,20			o/q/v	0,67	0,20	
Case 5: Residential building	c/v	81,7	o/q/v	1,00	0,17				o/q/v	0,71	0,17	o/q/v	0,91	0,17	c/q/v	0,83	0,17	c/v		o/q/v	0,70	0,17			o/q/v	0,75	0,17
Case 6: Residential building	c/v	82,0	o/q/v	0,91	0,17				o/q/v	0,96	0,17	o/q/v	0,89	0,17	c/q/v	0,67	0,17	c/v		o/q/v	0,70	0,17			o/q/v	0,79	0,17
Case 7.1: Residential building	c/v	58,3	o/q/v	0,71	0,17	o/q/v	0,43	0,17	o/q/v	0,43	0,17	o/q/v	0,89	0,17			c/v		o/q/v	0,50	0,17			o/q/v	0,54	0,17	
Case 7.2: Residential building	c/v	37,2				c/q/v	0,38	0,20	c/q/v	0,54	0,20	c/q/v	0,31	0,20			c/v		c/q/v	0,19	0,20			c/q/v	0,44	0,20	

6. BIM CASES

Case 1: A commercial building, 2-storey prefabricated reinforced concrete column-beam-slab frame commercial area; and 4-storey cast in-situ column-beam-slab car parking hall; pad and strip foundations. Structural BIM is at the detailed design stage in the beginning of construction works.

Case 2: A commercial building, 1-storey prefabricated steel column-beam-roof structure including also prefabricated reinforced concrete slabs, sandwich and wall panels, pile and pad and strip foundations. Structural BIM is at the procurement stage.

Case 3: A commercial building, 3-storey prefabricated reinforced concrete and steel column-beam-slab frame, sandwich and concrete panel walls, pad and strip foundations. Structural BIM is at the procurement stage.

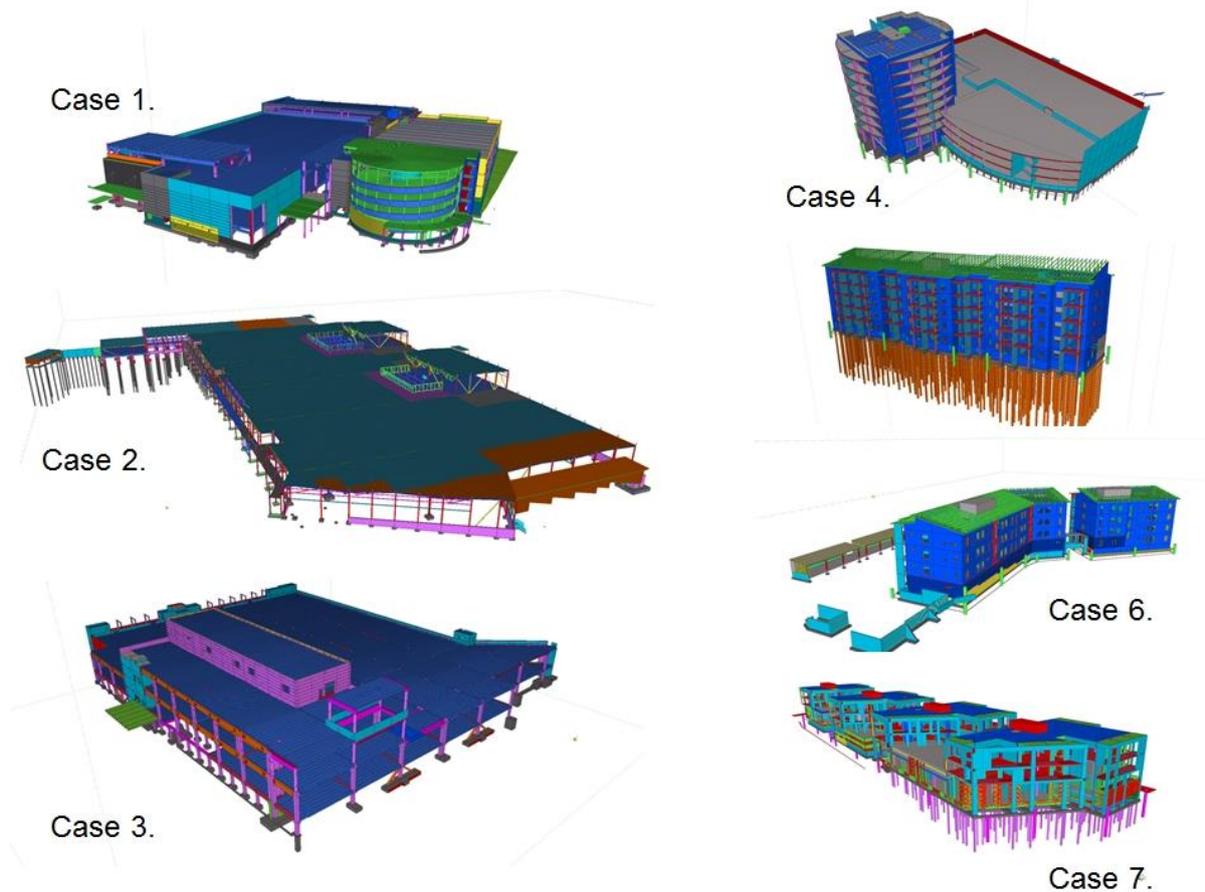


FIG. 2: Test cases

Case 4: A residential building, 8-storey apartment building, prefabricated reinforced concrete element frame (load-bearing walls, sandwich elements, hollow-core slabs); and 3-storey car parking hall, prefabricated concrete column-beam frame and in situ slabs; pile foundations. Structural BIM is at the procurement stage.

Case 5: A residential building, 8-storey apartment building, prefabricated reinforced concrete element frame (load-bearing walls, sandwich elements, hollow-core slabs); pile foundations. Structural BIM is at the detailed design stage in the beginning of construction works.

Case 6: Two residential buildings, 4-storey apartment building, prefabricated reinforced concrete element frame (load-bearing walls, sandwich elements, hollow-core slabs); strip foundations. Structural BIM is at the detailed design stage in the beginning of construction works.

Case 7.1: Four 4-storey residential buildings with commercial ground floors and car parking hall beneath ground level, load-bearing walls partly in situ concrete and prefabricated reinforced concrete elements, external walls sandwich elements, in situ slabs, pile foundations. Structural BIM is at the detailed design stage at the beginning of construction works.

Case 7.2: The same building as in the Case 7.1 but in the assessment is used an architectural BIM at the early design stage.

7. CASE RESULTS

Constructability scores of structural systems in analysed residential buildings (cases 4, 5, 6, and 7.1) vary from 58.3 to 82.0 and in analysed commercial buildings scores vary between 57.3 and 64.3. Constructability scores (CS) are shown in Table 3.

Analysing the key ratings of the constructability scores of elements (C_e , in Table 3.) and the BIM models visually, several differences were seen. The foundations of residential buildings got higher key ratings than commercial buildings. The foundations of residential buildings had been either on the same level or the variations between the levels of the foundation bed were minor. The number of foundation methods and types was also small. According to the commercial buildings, the foundation methods and types varied significantly. Furthermore, there was so much variation between the levels of foundation beds that weakened the constructability of foundations.

In the Case 6 the high standardization degree of columns is seen as quite a high key rating. The small key rating of columns in the Case 3 is caused by the big weight of columns (several more than 250 kN) and the low standardization of element and section types.

To the slabs good key ratings were obtained irrespective of the cases. The slabs were mainly prefabricated hollow-core elements in which the recurrence of types supposedly was high, and too long and heavy elements did not appear in the models.

The key ratings of external walls varied between 0.50 to 0.72, and load bearing walls varied from 0.54 to 0.79. The lowest key ratings were measured in a residential building in the Case 7.1. The reason for the low key rating of the constructability of walls is the high number of different element types, section profiles and height of walls.

The key rating of grids was the lowest in the Case 2 in which 2- and 3-dimensional steel grid frames were used. The element type, and height and length dimensions varied considerably. In residential buildings in the Cases 5 and 6 2-dimensional wooden trusses were used. The length and height and type of these trusses were repeated and were selected suitably for mass production in the wooden truss product factory used.

The key rating of joints could not be analysed because element and section types were not modelled. Reinforcements (CF4) were only partially modelled and were not taken in the assessment of constructability score. The area of holes could be quantified if a special hole or penetration object is used when the hole is modelled through building element. In the cases, the use of holes as hole objects in the model was still uncommon, and the constructability factor (CF6) was not used. Quantities for formwork (CF5) could be evaluated, but methods were not analysed and constructability factors were not formulated.

In the Case 7 (7.1 and 7.2) the constructability score was the lowest among the residential buildings. The interviews with contractor site managers and designer were carried on to get a deeper insight in the constructability of the building. The opinion of the site managers interviewed was that the constructability of the building was weaker than normally with residential buildings. So the constructability score introduced a good indication of the real constructability of these buildings. In the Case 7 clash checking software was used for analysing constructability visually. Integrated models (architectural, structural, MEP) were used. Because of the lack of assessment instructions and criteria the assessment work was time consuming and results were sporadic.

The models used for assessing constructability did not contain any information of construction work schedules, the order of assembly of elements, site layout plan or temporary assembly studs and scaffoldings. So as an important part of constructability factor areas could not take into consideration. According to the interviews, these were designed by the production model which was designed and maintained by the contractor's personnel.

8. DISCUSSION

Even though the need to assess constructability is evitable in a building project, the opinion of the necessity varies between project parties. The contractor's site and line managers need to assess the constructability in detail, because they are in the charge of, and responsible for the actual cost and quality of building works on site. Structural engineers have the other extremity of opinions not having any necessity for a separate constructability reviews in a project. This can be caused by the iterative and complementary character of designing work, and the methods used to inspect drawings. The designer may experience that he is working with constructability all the time. On the other hand, this can also be the consequence of the Finnish designing culture where special evaluation methods have not been used for assessing constructability, and a special need has not been recognized. Architects' and building service designers' views about constructability reviews were more neutral.

Both designers and contractors' site and line managers are used to assess constructability based on their previous professional skills and experiences. Because junior professionals lack experiences, they do not have the ability to assess constructability thoroughly. On the other hand junior professionals are able to use BIM better than senior professionals. In design projects, constructability was assessed mainly using drawings as a source of information. The correctness and clarity of drawings contributes to constructability but it is not enough because drawings should especially support construction works and performance on site. Building information model views, element reports and schedules extracted from BIM can be used to assess constructability and parameters affecting the constructability of building elements and systems. The use of BIM in reviews was becoming common gradually. Clash checking tools were used to analyse inconsistencies between and within design area specific BIMs and schedule of assemblies and safety on site (Sulankivi et al. 2014).

The assessment is carried out in stages and with varying participants in meetings. The points for the assessment of constructability were recognised at the schematic, building permit and design development stages. However, according to the present practice constructability is occasionally assessed during the design development stage and more systematically at the very end of the detailed design stage. However, the design process in Finland does not contain any specific meetings for constructability reviews at the moment. Quite general opinion was that at the moment constructability issues were discussed too late between designers and site managers. So the notices requiring for an efficient and fluent review process presented by building service designers, and the requests for an early participation in the review process announced by site managers should be considered in the development of design and construction process. The problem of timing the assessment of constructability was also recognized in the recent research done by Lam et al. (2012).

Constructability factors (CF1 to CF6) used in the experimental constructability assessment method (ECAM) were tentatively collected from the literature and the interviews. In the literature, there are only a limited number of articles, in which the effectiveness of design variables and factors for constructability are presented. Because the effectiveness of factors for the constructability is partly based on the tacit knowledge of interviewees, the researchers developed calculation equations and the rating system of the constructability factors to measure constructability score of elements. The selection of structural elements, the constructability of which was assessed, based on the pre-evaluation of the usability of BIM in the assessment, was similar to the elements reported by Fisher and Tatum (1997) and Alkass et al. (2009). The experimental constructability assessment method presented in this article deviates from BAM and SDBAM developed and tested in Hong Kong. The major difference is that BAM and SDBAM are based on the constructability ranking of common construction systems for example on the comparison between an in-situ reinforced frame a pre-cast reinforced concrete frame (Lam et al. 2007 and 2012). The ECAM using together with visual analysis of modelled elements gives more precise information on the constructability of elements than using BAM or SDBAM in the assessment, because each element as hollow core slab element, prefabricated wall panel or column can be evaluated separately and as a part of a structural system.

The values and the use of weight indexes (W_c and W_e) are in the decisive position to assessing the reliability of constructability score of the elements and the total constructability score of a building and a building type. For the key ratings of the constructability of elements (C_e) and constructability score (CS) a preliminary sensitivity analysis was made by varying the weight indexes of constructability factors (W_c) and the elements (W_e). The variation of weight indexes affected constructability scores. If someone assess constructability scores on the building element level (Equation 1, for example Foundations) in a building type (for example residential building type) to get insight into the differences between projects, the same constructability factors and weight

indexes should be used otherwise the scores are not proportional. If the constructability score (CS) differences of a building type are assessed on project level (Equation 2, Cases 5 and 6), the same structural element groups (foundation, columns, slabs, etc.) with the same weight index of elements should be taken into account.

In the Table 3, in all cases same constructability factors and weight indexes were used when the key rating of constructability scores of elements was calculated. Due to this, the key ratings of constructability score of elements (C_e) are comparable; for example Foundations $C_e = 0,48$ in Case 1 compared with $C_e = 0,67$ in Case 2, and the constructability of foundations in Case 2 is better than in Case 1. As observed in cases, when project level constructability scores (CS) were calculated element groups and corresponding weight indexes change case by case. For example, in Case 1 the number of the key ratings of constructability scores of elements (element groups) included is 6 ($W_e = 0,17$, $CS = 60,3$), and in Case 3 the number of the key ratings of constructability scores of elements included is 5 ($W_e = 0,20$, $CS = 57,4$), and element groups included are partly different. Due to this, the constructability scores on project level in a building type are only partially comparable among themselves. In this situation, sub-constructability scores on project level could be used. In cases of commercial buildings, Foundations, Beams, Columns, Slabs and External walls key ratings with weight index value 0,20 could be used in calculation, because element groups are common in all the projects, and calculated sub-constructability scores are 59,8 (Case 1), 72,2 (Case 2) and 57,4 (Case 3); that is, the constructability of Case 2 is better than in Cases 1 and 3.

In a design or construction company the principle of the use of the weight index should be standardized. The weights could be based on the importance of constructability factors and key ratings of constructability scores of elements or they could be set to have the same proportional value of total value. The weight index of building elements can be evaluated for example based on the costs of elements typical for the building type. Importance level could be evaluated in collaboration with the contractor and designers, so both parties can understand the connection between the constructability and design solutions in a particular construction project, which is the first step in enhancing constructability.

The proposed assessment methodology suggested in the article is an experimental one. It combines visual and analytical method in the review process of constructability using BIM as an information source. The assessment results can be calculated fast and the calculation can be repeated often. Constructability factors and their ratings must develop and test empirically more in the simulation studies and projects. Important constructability factor areas, should be taken into account, are site plan and earth works, scheduling and ordering of assemblies of elements, temporary assemblies and safety on site, all such subjects could be visualized in BIM.

9. CONCLUSION

At present, the assessment of constructability is not very consciously made by designers and contractor's site and line managers in Finland. The designers experienced that constructability could be assessed within the designing work without any separate assessment method or process. At the early design stage, the assessment is based on designers' professional skill and experience. Later at the design development and detailed design stages, contractor's site and line managers also involved in the constructability review process. Caused by the production managers' late participation constructability issues were discussed too late in the design process leading changes and extra work in design, delays in construction works and procurements of materials, and cost overruns. The contractor's site and line managers and ETO producer's managers would also like to take part in the review process in the earlier design stages. The main assessment method used is the inspection of drawings. All interviewed parties mentioned BIM as a tool that will be used more and more in the assessment of constructability.

The experimental constructability assessment methodology introduces the calculation method for building constructability scores based on the information content of structural BIM. Constructability scores of the building and building elements can be analysed. Describing ratings of constructability factors as equations used in the assessment method is an important precondition for a semi-automated assessment, combining visual and analytical information to support decision-making in building projects. Even the constructability score does not give any absolute real value for constructability, because it is not sufficiently empirically tested, it gives valuable pieces of information about the emerging constructability issues. The visual assessment of constructability using integrated BIMs is still cumbersome. This is caused by the missing evaluation criteria and the poorly planned review process in design development and detailed design stages. The use of clash checking is not enough for

constructability analysis in projects and the development of the assessment process will be needed. The results support the conclusion that the visual inspection with the calculation based screening method is applicable to the BIM-based constructability analysis of buildings and especially structural frames.

In Finland, there is a notable need for the development of an efficient review process for constructability assessment. Construction industry should be encouraged to use the assessment of constructability in projects also as a method for increasing the productivity of the building industry. In the building and design companies, the constructability scores and visual inspection of BIM guide designers and managers in charge of projects to identify factors improving or reducing constructability in a specific project. In the academic building education the education of constructability should be revised and researches combining constructability and the use of BIM should be encouraged.

At the moment experimental constructability assessment methodology is used in test cases and it is under the development. It is limited to assess the constructability of structural frames and elements. The items of the constructability that should be considered in the development are site plan and earth works, scheduling and ordering of assemblies of elements, temporary assemblies and safety on site. Architectural and building service design specific elements and systems can also be included in the assessment methodology.

10. ACKNOWLEDGEMENTS

The research is the part of work package “BIM-based product data management in the industrialized construction supply chain (BIMCON)” at Built Environment Process Re-engineering (PRE) program in Finland (2000-2014). The research was financed by RYM Oy and Tekes. In addition to the authors, the research team includes A-K. Mero, A. Lemström, M. Raikaa, P. Laakso, K. Forsblom and K. Koivu.

This article is based on the presented and published paper Tauriainen et al. (2014) in the Proceedings of the 10th European Conference on Product and Process Modelling (ECPPM 2014) in Vienna, Austria, 17-19 September 2014.

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