International Conference on Sustainable and Intelligent Manufacturing, RESIM 2016, 14-17 December 2016, Leiria, Portugal

The potential of decision support systems for more sustainable and intelligent constructions: a short overview

Nathalie Labonnote[a]*, Christofer Skaar[a], Petra Rüther[a]

aSINTEF Building and Infrastructure, PO Box 4760 Sluppen, NO-7465 Trondheim, Norway

Abstract

Up to now, the performance-based concept has been very rarely extended from engineering phase to other phases within the building process. To achieve more sustainable and more intelligent constructions, the construction industry needs decision support systems that integrate a selection of processes, constraints, time span, and performance criteria that are relevant to all involved stakeholders. This paper intends to demonstrate a design methodology that solves these challenges, and provides several frameworks for decision support systems deemed relevant to the construction industry. Examples of current applications are provided, together with a discussion on future opportunities. The possible synergy with new technologies is emphasized.

Keywords: performance-based design; construction industry; decision support tool; optimization, sensitivity analysis; design space exploration.

1. Introduction

1.1. Background

Until recently, the so-called prescriptive approach for building processes was in use, mostly for practical reasons: describing acceptable solutions makes the design easy to implement, its verification easy to perform, and regulations easy to enforce. However, Foliente [1] underlined that the prescriptive approach exhibited several serious problems:

---

* Corresponding author. Tel.: +47 93002052

 E-mail address: nathalie.labonnote@sintef.no

it serves as a barrier to innovation, it makes it very difficult to cost-optimize building construction, and it makes it difficult to compare products from two trading countries that use their own sets of criteria.

A relevant alternative is the performance-based design, which became famously known as "the practice of thinking and working in terms of ends rather than means" [2]. With other words, buildings and building products are thought of what they are required to do, rather than being prescribed how to be constructed. Today, the structural EUROCODES are the most comprehensive example of implementing the performance concept in formal design documents [3].

1.2. State-of-the-art

Spence and Kareem [4] stated that "Performance-based design is fast becoming the benchmark approach for achieving designs that rationally meet society's need for a truly safe built environment". However, appropriate frameworks that allow the principles of performance-based design to be adopted have been mostly restricted to structural engineering of specific types of constructions: e.g. tall buildings [5], to specific construction materials: e.g. concrete [6], or to specific structural requirements: e.g. seismic analyses [7] or wind excitation [8]. Some few studies attempted to combine several engineering disciplines for performance-base design. Among others, Becker [3] considered fire safety, acoustics, moisture safety, indoor air quality and durability in order to formally map the user needs and performance requirements. More recently, Brown and Mueller [9] used simultaneously structural modeling and building energy simulations to generate optimized building shapes.

In general, most multi-disciplinary studies investigated the environmental performance of construction. Caldas and Norford [10] proposed a tool to optimize design solutions in terms of thermal and lighting performance. Later, Ochoa et al. [11] determined the suitability of combined optimization criteria on window sizing procedures for low energy consumption and high visual comfort. Wang et al.[12] presented a methodology to optimize building shapes in plan by considering both life-cycle cost and life-cycle environmental impact. Fabrizio et al. [13] customized their modelling approach to integrate different energy sources in order to cover the thermal and electrical loads of a building. Nguyen et al. [14] gave a complete review on "building design optimization", although the scope of their work was limited to the design of "greener" buildings, without taking into account other types of requirements. At the same time, there is a recognized lack of suitable tools for early design of for example environmental objectives [15, 16].

Up to now, the performance-based concept has been very rarely extended from engineering phase to other phases within the building process, particularly those occurring after the construction, although they may have a substantial effect on the required level of investment. The whole building process is still following a very linear workflow despite studies that suggest to enhance interdisciplinary in order to reduce the investment in poor performing solutions [17].

Despite the strong need for highly efficient structures motivated by rapidly decreasing resources and high construction costs, structural optimization methods that prioritize efficiency have not taken hold in practice [18]. Bakens, Foliente and Jasuja [19] insisted on the fact that to engage stakeholders effectively, the performance approach should be presented as a business issue rather than primarily as a technical issue. Cost is maybe the most crucial business issue: e.g. Marks [20] determined the optimal dimensions of a building by minimizing the building and heating costs. However, environmental issues are increasingly studied at the design phase: e.g. Fesanghary et al. [21] attempted to satisfy the multiple objectives of energy consumption optimization, financial costs reduction and decrease of environmental impacts. Other important business issues, e.g. construction time, health and safety, and societal cost, have been very seldom investigated within such frameworks. In general, eliciting the needs and requirements of all stakeholders is necessary, as these may not be aligned [22].

1.3. Main motivation and objectives

Decision support systems should intend to integrate a selection of processes, constraints, time span, and performance criteria that are relevant to all involved stakeholders. The "design team", which is usually limited to architects and engineers, should instead encompass also manufacturers, entrepreneurs, future owners, users, etc and should make use of the "performance-based design" concept in a very broad sense.

This paper intends to demonstrate a design methodology that solves these challenges. A framework for a decision support system is provided; the novelty of this approach lies in the extended scope of processes that are taken into account and in the extended amount of performance indicators that are deemed relevant to contribute to a global definition of performance of a construction (see Fig. 1).

This paper has the following objectives:

- to provide a short state-of-the-art on the development of performance-based design, and its current limitations,
- to formally establish some frameworks for simulation tools and for decision support systems,
- to provide examples of current and future applications within the construction industry of such frameworks,
- to discuss the opportunities of such frameworks within the construction industry in light of some recent technological advances.
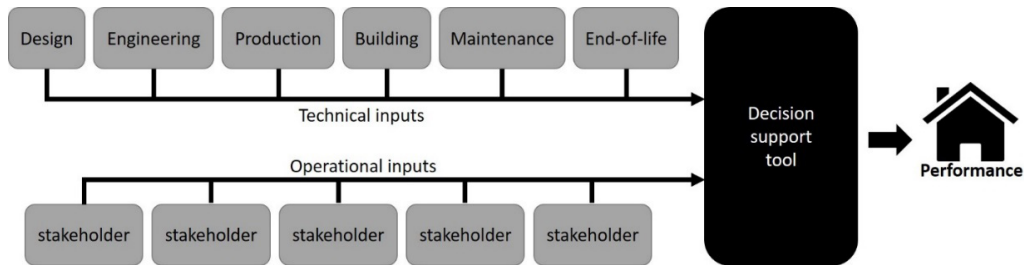

Fig. 1. An extended scope for performance-based design as a framework for a decision support tool

2. Multi-process simulation framework

2.1. Scope: to provide data

The motivation for developing a multi-process simulation framework is to deliver the most complete performance picture of a given construction (see Fig. 2). All available knowledge needs to be incorporated into the tool, so that:

- It enhances coordination inside the design team and facilitates the dialog between experts and non-experts.
- The whole simulation platform can be re-used for other projects, either partly or completely.
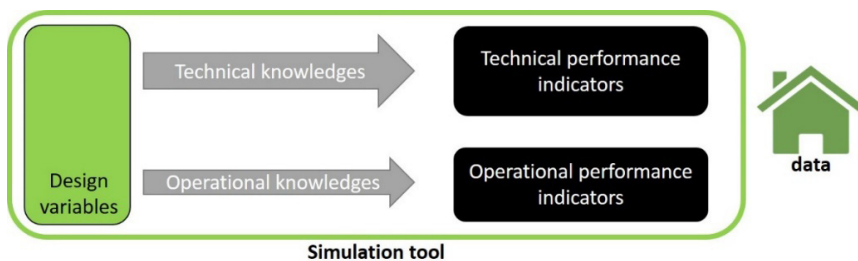

Fig. 2. Framework for a multi-process simulation tool (input = design variables, output = performance data)

2.2. Building steps

Building a multi-process simulation framework requires the following steps (see Fig. 2):

- Determine the relevant design variables. Design variables are defined as quantities describing the construction.

- Define the relevant performance indicators, which could be of two types (see Fig. 1):
  - o Technical performance indicators arise from the building process: e.g. U-value from thermal analyses, load-bearing capacity from structural analyses, or damping properties of building products.
  - o Operational performance indicators arise from stakeholders, and are mostly related to business issues: e.g. life-cycle cost, carbon footprint, societal cost, or health and safety metrics.
- Map and digitize the available knowledge. Knowledge can be defined as a "rule" – i.e. a simplified equation or a complex model – that transforms a set of design variables into one or several performance indicators.

3. Extensions to a decision support system framework

3.1. Scope: to provide knowledge

Simulation tools answer the need for accurate quantitative performance results, but they do not provide any evaluation of the provided data. Mueller and Ochsendorf [18] observed that to overcome this lack of knowledge, designers are tempted to use simulation tools in a time-consuming trial-and-error mode. By doing so, they limit the number of design alternatives and reduce the quality of the chosen solution. The complexity of real-world design problems requires decision support tools that also integrate optimization, analysis, and modeling [23] in order to give involved stakeholders an increased knowledge on the design space instead of data from a single construction. At the same time, this should also make the process more attractive to architects searching for creative forms [9].

3.2. Sensitivity analyses

Sensitivity analyses may be performed to screen out insignificant variables (see Fig. 3). Several sensitivity analysis techniques can be used such as local sensitivity analysis methods, screening methods, Monte Carlo-based methods, variance-based methods or ''design of experiment'' methods [14].
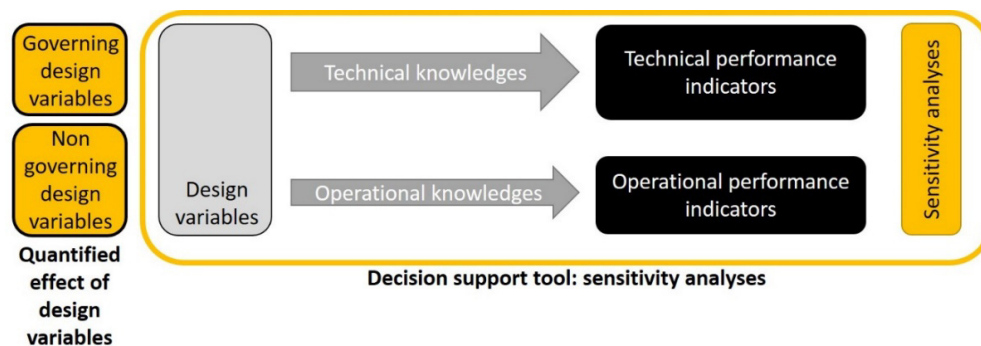

Fig. 3. Framework for sensitivity analyses (output = distinction between governing and non-governing design variables)

3.3. Multi-criteria optimization

Building a multi-criteria optimization system (see Fig. 4) requires the following steps (most of the definitions are adapted from Marks [20]):
- Determine decision variables. Decision variables are defined as the set of design variables that will be subjected to variations during the optimization process.
- Determine design constraints. Design constraints describe certain conditions to be satisfied by a construction and usually occur in the form of equalities or inequalities. They are imposed on decision variables to

determine the boundary of the feasible region. They highly depend on the context and are construction-specific.

- Determine performance constraints. Performance constraints describe certain conditions to be satisfied by a construction and usually occur in the form of equalities or inequalities. They are imposed on performance indicators. Technical performance constraints generally consist in technical requirements originating from official standards, code, or internal specifications. Operational performance constraints can be related to the ambition level or definitive stakeholder requirements, for example cost or environmental performance.
- Determine a set of objective functions. An objective function is a mathematical expression describing a wanted property of the construction, and usually consists in setting a target, e.g. maximize or minimize, to performance indicators. The set of objective functions is called the objective function vector.
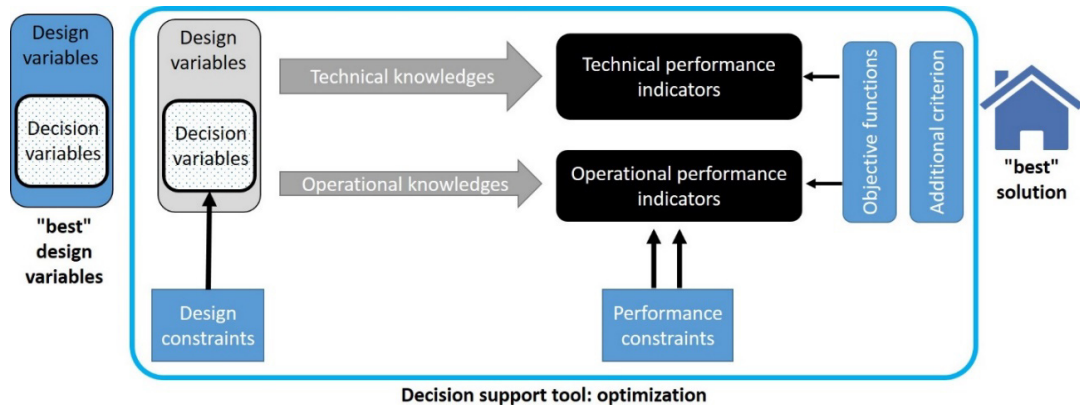

Fig. 4. Framework for optimization methods (output = "best" solution and its corresponding set of decision variables)

Solving a multi-criteria optimization problem leads to different types of solutions:
- The ideal solution of an optimization problem is the solution which makes every objective function reach its extremum independently of the remaining functions. The ideal solution does not exist in most cases as objective functions are usually in conflict.
- The non-dominated solution set is defined as a compromise set, where none of the objective functions can be improved without simultaneous deterioration of at least one of the remaining objective functions.
- The preferred solution is defined as one solution from the non-dominated solution set, selected on the basis of an additional criterion.

3.4. Multi-objective design space exploration

Optimization produces a single solution to a design problem [18]. However, an ideal decision support tool (see Fig. 5) should expose involved stakeholders to a diverse range of alternatives that may inspire new goals or spark new ideas. Among other design space exploration approaches, evolutionary algorithms aim at replicating biology: a child inherits good traits from both parents while exposed to the possibility for mutation for generating biodiversity. Evolutionary algorithms consists in two main parameters:
- The generation size is defined as the number of candidate designs evaluated after a step of evolutionary exploration. It reflects a tradeoff between high performance and limited computation time.
- The mutation rate is introduced as a degree of randomness when a new population of designs is generated. A high mutation rate gives the ability to move around the design space quickly, whereas a low mutation rate ensures that positive traits inherited from parents are effectively passed on to children.

Mueller and Ochsendorf [18] proposed a new computational approach for design space exploration that includes qualitative performance criteria – i.e. non-measurable goals – via a direct impact on the mutation rate. In other words, involved stakeholders decide which designs should become parents for the next generation. Hamacher and Kjølsrud [24] evaluated the benefits of similar tools in the early investigative design phase, and concluded on the need of helping involved stakeholders to "think out-of-the-box". Finally, Magnier and Haghighat [25] showed that revealing a multitude of design options provides stakeholders with better decision support
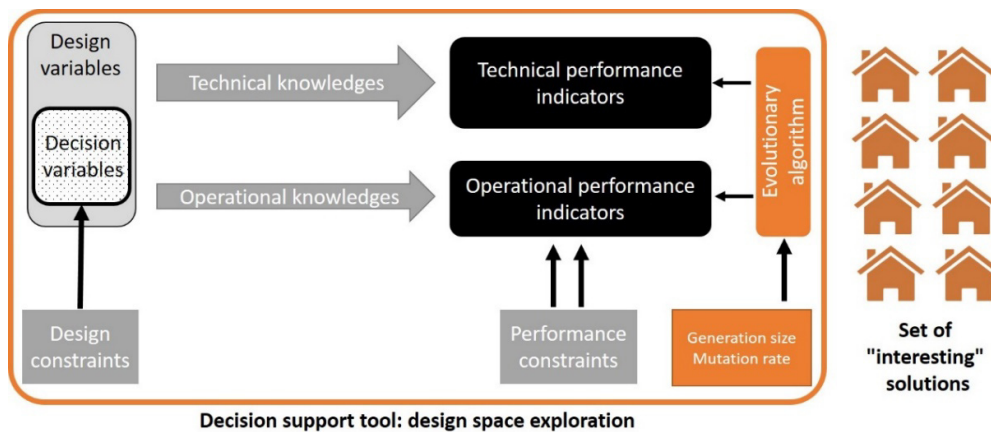

Fig. 5. Framework for design space exploration methods (output = set of "close-to-optimal" interesting solutions)

3.5. Selection of current applications

Tall Timber facades [26] is a European research project that aims at facilitating confident design of durable and cost-effective solutions for tall timber facades. The project consortium is developing a risk-based design tool taking into account exposure and vulnerability of façade components and systems [27]. The tool will enable planners and producers to make substantiated decisions for specific constructions. WoodSols [28] is a Norwegian research project that aims at increasing the use of wood in urban areas. Solutions should then be suitable for industrial scale production and should be able to be used in large and flexible buildings. Skaar et al. [29] are currently evaluating the potential of low-carbon timber-concrete composite floors with the challenge of meeting structural, safety and acoustic requirements. Moelven Orkdal bridges is a Norwegian innovation project that intends to build a framework for linking architects, engineers, timber element producers, steel connection producers, and final owners. The construction typology is the one of truss timber pedestrian bridges of short span [30].

4. Challenges, opportunities and future applications in the light of recent advances in new technologies

The building research community has demonstrated a great interest in building optimization studies for the last two decades [14]. Although Jato-Espino et al. [31] provided an overview of a number of multi-criteria decision making methods in the construction industry, the applications of decision support systems for real-world design challenges are still in the early stage of development. One of the main challenges is their actual adoption by end-users. This limited use in practice has often been observed [32], and the identified reasons include:
- the development of highly specialized software products tailored to handle particular profession-specific needs [33] induces complicated communication within an unified framework,
- the linear building process results in that members of the design team are only given small latitude to "optimize" for their own performance goals without reference to other disciplines [32] or system levels [34],
- non-quantitative preferences and design goals are difficult to include in optimization frameworks [18, 32],

- several technical obstacles in coupling strategies, usability, flexibility and efficiency (i.e. in term of both time and performance improvement) partly inhibit the propagation of optimization techniques in building design practice [14],
- the difficulty of targeting the actual needs of the end-users makes it challenging to find a trade-off between abstraction of the technical complexity while maintaining a sufficient level of flexibility [23],
- the challenge that requirements vary under different conditions, e.g. regulatory conditions [35] makes it difficult to develop suitable tools, and
- the absence of validated models that address the performance of the construction over its whole life cycle, for example durability of building materials [36].

The development of decision support tools for the construction industry will likely benefit from recent advances in "intelligent" [37] technologies, as more usable data and more useful knowledge will be produced. The construction industry already deals with large volumes [38, 39] of heterogeneous data; this is expected to increase exponentially as technologies such as sensor networks and the Internet of Things are developed [40]. Big Data is the ability to process such large amounts of data and to extract useful insights from it, and it has applications for a wide assortment of industries, including the construction industry [40]. Finally, Artificial Intelligence is demonstrating new possibilities in the way computers can inform and actively interact with the design process [10].

When it comes to future applications, the development of robotics and additive manufacturing technologies have been recognized to have the potential to revolutionize the construction industry [41]. Within the described frameworks, these technologies act as a source for digital technical knowledge related to production processes and to material selection processes. However, verified and comprehensive studies on the profitability or on the real environmental impact of additive manufacturing for the construction sector are missing [42]. Decision support frameworks with extended scope are necessary for such evaluations, and they would help to develop further innovative constructions.

Skaar and Norby [43] claimed that circular economy could address the need for reducing the carbon footprint by 70-100% in the building and construction industry without significantly increasing other environmental or social impacts in a life cycle perspective, and they presented a framework for analyzing business models for reuse and recycling of building components and building materials. In general, the implementation of circular economy knowledge into decision support systems would benefit the construction industry as a means for boosting global competitiveness, for fostering sustainable economic growth and for generating new jobs.

5. Summary and conclusions

There is a substantial demand for more sustainable and more intelligent construction, but the linearity of the building process is a strong inhibitor of design innovations. The construction industry needs to take better-informed decisions for developing more performant and more innovative designs and processes. Increased knowledge can be provided by the use of decision support tools that encompass a wide range of performance criteria. Frameworks for such decision support tools, suitable for the construction industry, are formally defined in this paper. Definitions are generic enough to be applied to any construction project and any building process. The necessity of such tools is likely to increase substantially when it comes to evaluate the benefits of new technologies for the construction industry in a systematic – and objective – way. This paper is intended to foster and support innovation within the design and building processes, and to provide the necessary frameworks for a more systematic definition and evaluation of "sustainable" and "intelligent" constructions.

Acknowledgements

References

[1] G.C. Foliente, Developments in performance-based building codes and standards, Forest Products Journal, 50 (2000) 2-11.

[2] International Council for Building Research Studies and Documentation, Working with the performance approach in building, in: Working Commission 60 (Ed.), CIB, 1982.

[3] R. Becker, Fundamentals of performance-based building design, Building Simulation, 1 (2008) 356-371.

[4] S.M.J. Spence, A. Kareem, Performance-based design and optimization of uncertain wind-excited dynamic building systems, Engineering Structures, 78 (2014) 133-144.

[5] M.N. Aydinoğlu, Challenges and Problems in Performance-Based Design of Tall Buildings, in: Geotechnical, Geological and Earthquake Engineering, 2014, pp. 279-300.

[6] A. Younsi, P. Turcry, E. Rozire, A. Aït-Mokhtar, A. Loukili, Performance-based design and carbonation of concrete with high fly ash content, Cement and Concrete Composites, 33 (2011) 993-1000.

[7] Y. Lu, I. Hajirasouliha, A.M. Marshall, Performance-based seismic design of flexible-base multi-storey buildings considering soil-structure interaction, Engineering Structures, 108 (2016) 90-103.

[8] M.F. Huang, C.M. Chan, W.J. Lou, Optimal performance-based design of wind sensitive tall buildings considering uncertainties, Computers and Structures, 98-99 (2012) 7-16.

[9] N.C. Brown, C.T. Mueller, Design for structural and energy performance of long span buildings using geometric multi-objective optimization, Energy and Buildings, 127 (2016) 748-761.

[10] L.G. Caldas, L.K. Norford, A design optimization tool based on a genetic algorithm, Automation in Construction, 11 (2002) 173-184.

[11] C.E. Ochoa, M.B.C. Aries, E.J. van Loenen, J.L.M. Hensen, Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort, Applied Energy, 95 (2012) 238-245.

[12] W. Wang, H. Rivard, R. Zmeureanu, Floor shape optimization for green building design, Advanced Engineering Informatics, 20 (2006) 363-378.

[13] E. Fabrizio, V. Corrado, M. Filippi, A model to design and optimize multi-energy systems in buildings at the design concept stage, Renewable Energy, 35 (2010) 644-655.

[14] A.T. Nguyen, S. Reiter, P. Rigo, A review on simulation-based optimization methods applied to building performance analysis, Applied Energy, 113 (2014) 1043-1058.

[15] G. Lamé, Y. Leroy, B. Yannou, Ecodesign tools in the construction sector: Analyzing usage inadequacies with designers' needs, Journal of Cleaner Production, 148 (2017) 60-72.

[16] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of buildings: A critical review, Renewable and Sustainable Energy Reviews, 67 (2017) 408-416.

[17] M. Turrin, P. Von Buelow, R. Stouffs, Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms, Advanced Engineering Informatics, 25 (2011) 656-675.

[18] C.T. Mueller, J.A. Ochsendorf, Combining structural performance and designer preferences in evolutionary design space exploration, Automation in Construction, 52 (2015) 70-82.

[19] W. Bakens, G. Foliente, M. Jasuja, Engaging stakeholders in performance-based building: Lessons from the Performance-Based Building (PeBBu) Network, Building Research and Information, 33 (2005) 149-158.

[20] W. Marks, Multicriteria optimisation of shape of energy-saving buildings, Building and Environment, 32 (1997) 331-339.

[21] M. Fesanghary, S. Asadi, Z.W. Geem, Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm, Building and Environment, 49 (2012) 245-250.

[22] R.E. Freeman, Stakeholder theory: the state of the art, Cambridge University Press, New York, 2010.

[23] I. Chatzikonstantinou, A computational intelligence decision-support environment for architectural and building design: CIDEA, in: 2016 IEEE Congress on Evolutionary Computation, CEC 2016, 2016, pp. 3887-3894.

[24] E. Kjølsrud, A. Hamacher, Growing floor plans and buildings -generation and optimisation through algorithms and synthetic evolution, in: 2nd International Conference Of Biodigital Architecture & Genetics, 2014.

[25] L. Magnier, F. Haghighat, Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network, Building and Environment, 45 (2010) 739-746.

[26] Tall Timber Facades consortium; Identification of Cost-effective and Resilient Envelopes for Wood Constructions; http://fungi.tallfacades.eu/; 2017

[27] K. Gradeci, N. Labonnote, B. Time, J. Köhler, A proposed probabilistic-based design methodology for predicting mould occurrence in timber façades, in: Nordic Symposium on Building Physics, Trondheim, Norway, 2017.

[28] The Norwegian University of Science and Technology; WOOD Frame SOLutions for free space design in urban buildings; www.woodsol.no; 2017

[29] C. Skaar, B. Solem, P. Rüther, Composite floors in urban buildings: Options for a low carbon building design, in: 6Th Forum Wood Building Nordic Trondheim, Trondheim, Norway, 2017.

[30] J. H. Mork, M. Luczkowski, A. Rønnquist, N. Labonnote, An efficient framework for advanced timber structure designs, in: 3 rd International Conference on Timber Bridges, Skellefteå, Sweden, 2017.

[31] D. Jato-Espino, E. Castillo-Lopez, J. Rodriguez-Hernandez, J.C. Canteras-Jordana, A review of application of multi-criteria decision making methods in construction, Automation in Construction, 45 (2014) 151-162.

[32] N. Brown, S. Tseranidis, C. Mueller, Multi-objective optimization for diversity and performance in conceptual structural design, in: Proceeedings of the International Association for Shell and Spatial Structures (IASS) SYmposium 2015, Amsterdan, The Nederlands, 2015.

[33] N. Labonnote, J.H. Mork, A. Gunleiksrud, A. Rønnquist, B. Manum, Trondheim HolzBau Pier; The Elegance of Efficiency, IABSE Symposium Report, 104 (2015) 1-8.

[34] E. Fraile-Garcia, J. Ferreiro-Cabello, E. Martinez-Camara, E. Jimenez-Macias, Adaptation of methodology to select structural alternatives of one-way slab in residential building to the guidelines of the European Committee for Standardization (CEN/TC 350), Environmental Impact Assessment Review, 55 (2015) 144-155.

[35] P. Rocha, M. Kaut, A.S. Siddiqui, Energy-efficient building retrofits: An assessment of regulatory proposals under uncertainty, Energy, 101 (2016) 278-287.

[36] A. Grant, R. Ries, Impact of building service life models on life cycle assessment, Building Research & Information, 41 (2013) 168-186.

[37] Gartner, Gartner top 10 technology trends, in, 2017.
[38] R. Marsh, LCA profiles for building components: strategies for the early design process, Building Research & Information, 44 (2016) 358-375.
[39] J. Heinonen, A. Säynäjoki, J.-M. Junnonen, A. Pöyry, S. Junnila, Pre-use phase LCA of a multi-story residential building: Can greenhouse gas emissions be used as a more general environmental performance indicator?, Building and Environment, 95 (2016) 116-125.
[40] M. Bilal, L.O. Oyedele, J. Qadir, K. Munir, S.O. Ajayi, O.O. Akinade, H.A. Owolabi, H.A. Alaka, M. Pasha, Big Data in the construction industry: A review of present status, opportunities, and future trends, Advanced Engineering Informatics, 30 (2016) 500-521.
[41] N. Labonnote, A. Rønnquist, B. Manum, P. Rüther, Additive construction: State-of-the-art, challenges and opportunities, Automation in Construction, 72, Part 3 (2016) 347-366.
[42] N. Labonnote, P. Rüther, Additive manufacturing: an opportunity for functional and sustainable constructions, in: Smart and Sustainable Manufacturing, Lisbon, Portugal, 2016.
[43] C. Skaar, A.S. Nordby, Business models for sustainable resuse and recycling: the case of the Norwegian construction sector, (2016).