

# COMPLEXITY IN DESIGNING ENERGY EFFICIENT BUILDINGS: TOWARDS UNDERSTANDING DECISION NETWORKS IN DESIGN

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## ABSTRACT

Most important decisions for designing energy efficient buildings are made in the early stages of design. Designing is a complex interdisciplinary task, and energy efficiency requirements are pushing boundaries even further. This study analyzes the level of complexity for energy efficient building design and possible remedies for managing or reducing the complexity. Methodologically, we used the design structure matrix for mapping the current design tasks and hierarchical decomposition of life-cycle analysis for visualizing the interdependency of the design tasks and design disciplines and how changes propagate throughout the system, tasks and disciplines.

We have visualized the interdependency of design tasks and design disciplines and how changes propagate throughout the system. Current design of energy efficiency building is a linear and one-shot approach without iterations planned into the process. Broken management techniques do not help to reduce the complexity.

## KEYWORDS

Design structure matrix, design process, process models and modelling, complexity.

## INTRODUCTION

Most important decisions are made in the early stages of design, influencing the energy certification levels that can be obtained (Pikas, Thalfeldt, and Kurnitski, 2014). Macleamy's curve is often used for explaining and describing this concept (Eastman, et al., 2011). Designing of civil structures is becoming more complex in terms of technology, technical solutions, organization and its processes. Energy efficiency requirements are pushing these boundaries even further.

Currently, much design energy or resources are spent at the design development and construction documentation stages with the focus on drawing production. Design processes are organized in a sequential and concurrent manner rather than in terms of lean production (Ballard and Koskela, 1998; Ballard, 2000; Morgan and Liker, 2006),

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to reduce the duration of overall design. Many of the problems faced are not caused by designers and engineers, but by prevailing disjointed management (Pikas, et al., 2015) and contracting methods (Howell, Ballard and Tommelein, 2010). Due to budget and schedule constraints, down-stream designers and engineers are not systematically involved in up-stream decision making (Reed, 2009). However, a need for design change amounts into huge rework due to batch and linear nature of design processes. Many of these changes are initiated by the client and/or the architect, influencing other engineering disciplines. Therefore, building design is a complex and multi-objective task, as decisions made by different disciplines influence others.

The purpose of this research is to determine the complexity levels involved in energy efficient building design and possible solutions for managing or reducing the complexity. We visualize how changing architectural solutions influence other engineering disciplines and the energy efficiency and life-cycle costs of the facility. Then, current understanding of design complexity is summarized, and the methods chosen for this research are described, results are presented with possible methodologies discussed for reducing design complexity.

## **WHAT DOES COMPLEXITY MEAN IN BUILDING DESIGN?**

What does a complex system mean? The term ‘complex’ is often loosely used and its meaning seems to be rather vague. In literature, discussions on complexity are generally divided into three broad categories: product (Suh, 2001; Lee, 2003), process (Eppinger and Browning, 2012) and organization/people (Bertelsen and Emmitt, 2005; Snowden and Boone, 2007). In this article, the main focus is on process complexity, but we also review product and organizational complexity.

### **PROCESS COMPLEXITY**

Bertelsen has argued that construction production and client must be seen as a complex system (Bertelsen, 2003a; Bertelsen, 2003b; Bertelsen and Emmitt, 2005). Taking this discussion further, we need to differentiate between construction and design stages. Pennanen and Koskela (2005) have argued that the design problems are inductive in nature and that there is no single best answer but rather either a good or a bad one; but construction is deductive, i.e., there can be one best answer. Theoretically, in construction simple and ordered systems could be developed with sequential or concurrent tasks (Pennanen and Koskela, 2005). Hence, complexity is rather self-inflicted and caused by organizational structures and people (Tommelein, 2015). Tasks in design are driven by product considerations, which means that in every stage and/or phase, a designer executes tasks that produce product related information required for subsequent tasks – information is flowing (Koskela, Huovila and Leinonen, 2002). What makes design complex is that two or more tasks are coupled (Wynn, 2007) and simultaneously need input from each other.

### **PRODUCT COMPLEXITY**

Lee (2003) has discussed the meaning of complexity in the context of axiomatic (Suh, 2001) and engineering design. He infers that complexity is a property of a system that makes understanding of it difficult. Reed (2009) has compared a building with an “organism” and has stated that like a human body, a building could also be seen as a complex system. These systems have emergent behavior and not all of the causal

relationships between systems and systems' elements are understood, which limits the capability of predicting its behavior (Suh, 2001). In engineering design, many statistical correlations are used for doing design and engineering. For example, engineers use statistical averages for building occupation and usage profile or use correlational models for predicting domestic hot water need when calculating energy efficiency for certification.

## **METHODS**

This research is divided into the following steps: we analyze the current design process by using the Design Structure Matrix (DSM); we decompose the life-cycle analysis (Net Present Value, NPV) calculations into its constituent parts. Based on the understanding of the current design processes and the NPV, we have developed a scenario for visualizing how changing architectural solutions influence and propagate throughout the whole building system; and finally, we discuss the possible implications and future research prospects.

### **DESIGN STRUCTURE MATRIX**

In this research, DSM is used for mapping and modelling design tasks related to a specific design stage and discipline. DSM, developed by systems engineers, is used for understanding how engineered structures, processes and organizations are realized through assembly of sub-systems and its elements/components (Steward, 1981; Eppinger and Browning, 2012).

The list of tasks and abbreviations for energy efficient building design (see Appendix 1) has been compiled by observing and interviewing a whole service design office in Estonia. The list of stages, tasks and their dependencies were verified by comparing it to the Estonian national "Building Design" standard (ECS, 2012), legislations (Office, 2012) and guidelines. Subsequently, the Cambridge design modelling application was used for visualizing and optimizing the design process (Wynn, 2007).

### **HIERARCHICAL DECOMPOSITION OF LIFE-CYCLE ANALYSIS**

We used a hierarchical decomposition of the NPV to understand which information and tasks are related, as shown in Figure 1. The NPV itself is a multi-variable value encompassing hierarchically many different decisions made by different disciplines during various stages and with varying level of detail. It is a life-cycle analysis method that enables comparing different design alternatives, i.e., initial energy performance related investment to whole life-cycle energy savings to find a balance between these over the life-cycle of a building (usually 20 years for non-residential and 30 years for residential buildings). The NPV methodology is most widely used by the energy efficiency and sustainability research communities (Kurnitski and Group, 2013).

This helped to understand how the different design functions (dependent variables) and design parameters (independent variables) are related to each other. This decomposition can be compared to zigzagging in the axiomatic design concept - functional breakdown of the product and mapping of design parameters to these functions (Suh, 2001). The designer is describing an artefact in functional terms and maps these to the physical domain (possible physical structure of the artefact).

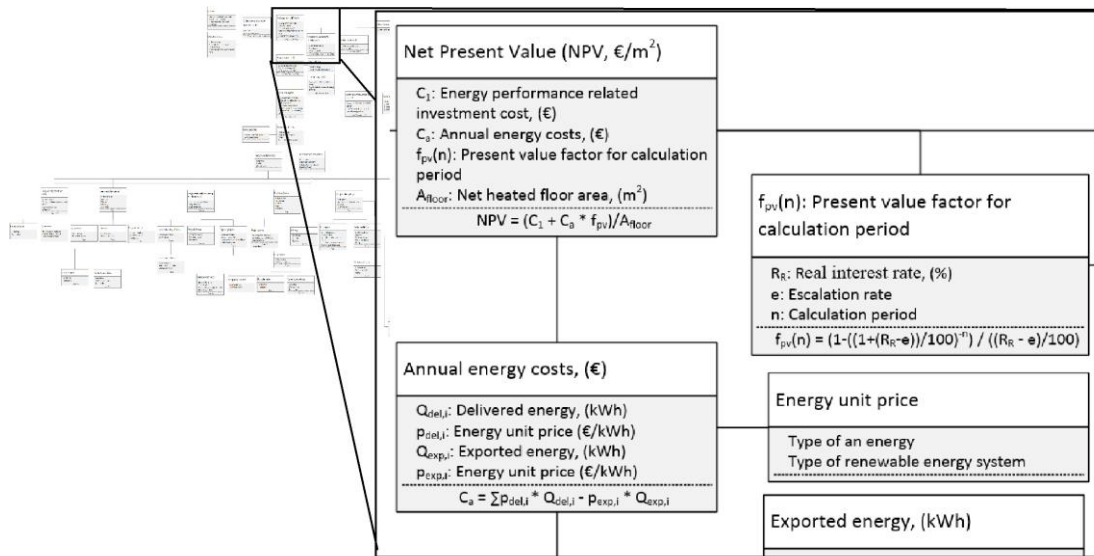


Figure 1. Overall model for the calculation of the life-cycle cost.

## DESIGNING ENERGY EFFICIENT BUILDINGS: DSM MODELLING

### CURRENT AND OPTIMIZED DESIGN PROCESSES

Figure 2 shows the typical design process for designing the energy efficient buildings. It demonstrates the dominating role of an architect in the early stages of design to close the spatial design or form and shape before solving engineering problems. The DSM diagram also illustrates the batch nature of design; engineers start to work in their batches after the architect has finished. For closing the sequence, the building services engineer enters again to perform the energy efficiency calculations for certifying the energy use level. If the simulation results show that the current design solution meets neither minimum nor client requirements, serious consequences may result. When the client has set only the minimum energy efficiency requirements defined by legislation, typically no problems arise. However, when the client demands higher energy efficiency, for example, a low energy building (B-class), then a typical procedure or sequence of the building services engineer for improving energy efficiency is as follows:

- Identify if more efficient equipment, for instance, heating, ventilation or cooling can help to meet the required efficiency level.
- If not, recommend alternative solutions to the architect, which have minimum influence on the architectural solution (e.g. better windows, more insulation etc.).
- If the energy efficiency level is still not met, then local energy production may provide the solution if they are able to help meet the required efficiency level.
- If not, only in that case reconsider redesigning the architectural shape and form.

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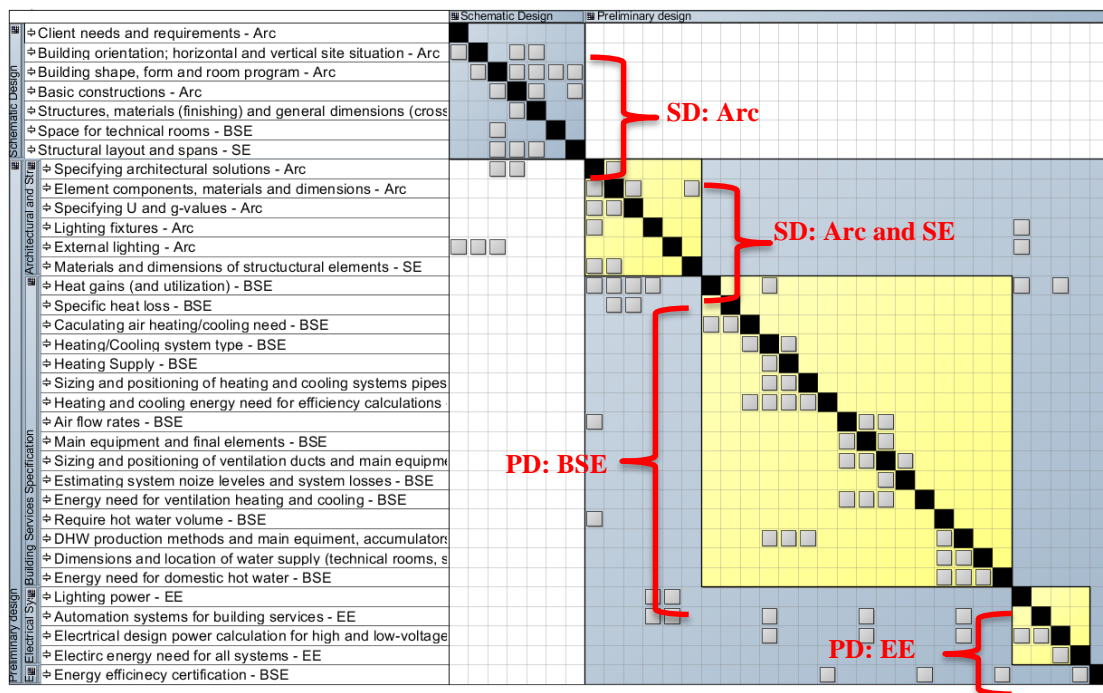


Figure 2. Typical design process.

Therefore, typically the design team prefers to keep the negative feedback loop as short as possible. The longer the negative iteration, the more rework must be done. Secondly, the typical design process presented in the figure above illustrates that the process is already well optimized, as not too many marks are present above the diagonal. As a result of interviews with a project manager, an architect, and structural, building services and electrical engineers, it was found that the current strategy for reducing interdependencies and rework between tasks is standardization and buffering.

Figure 3 shows optimized processes for energy efficient building design. In the next step, we used the DSM partitioning algorithm to reduce or eliminate feedback loops by delaying some of the tasks, as shown in Figure 2 (Eppinger, 1991). The aim was to reduce the complexity by uncoupling or decoupling design tasks. In simple terms, the aim was to reduce the marks above the diagonal by transforming the DSM into a lower triangular form or moving them as close as possible to the diagonal. After applying the algorithm, overall the process remains the same with slight changes, only the building services engineer and the electrical engineer are supposed to work more closely to define automation and nominal system powers, i.e., electric energy needs.

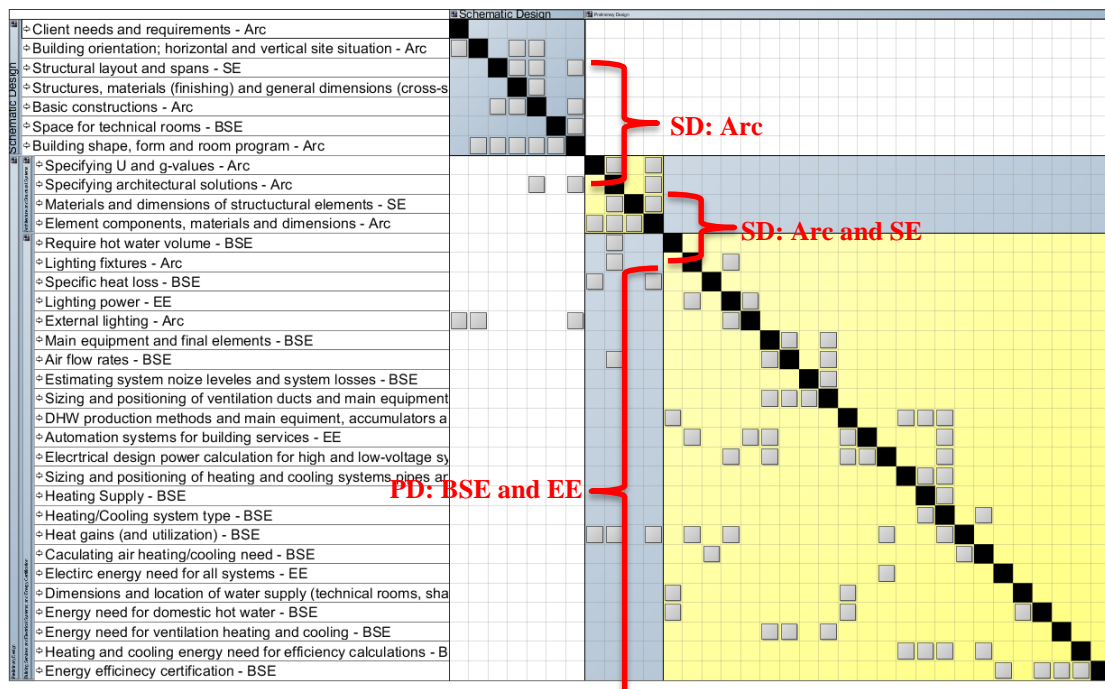


Figure 3.: Typical design process after partitioning for optimizing the design process.

## DESIGN SCENARIO AND ITS IMPACT ON THE DESIGNED ARTEFACT

The design scenario is used to determine the relationships between the design parameters, design tasks and disciplines by how building geometry changes during the design development stage influence these aspects.

### LATE CHANGE IN BUILDING GEOMETRY

Figure 4 illustrates the impact of changing the building geometry. As can be seen, it changes compactness and the main characteristics of the building (such as areas, design air flow rates, specific heat loss, etc.). This in turn influences the systems, therefore, also energy need and energy delivered, with the production of local renewable energy subtracted. Finally, all this influences construction and annual energy costs, leading to a new NPV of the proposed design solution.

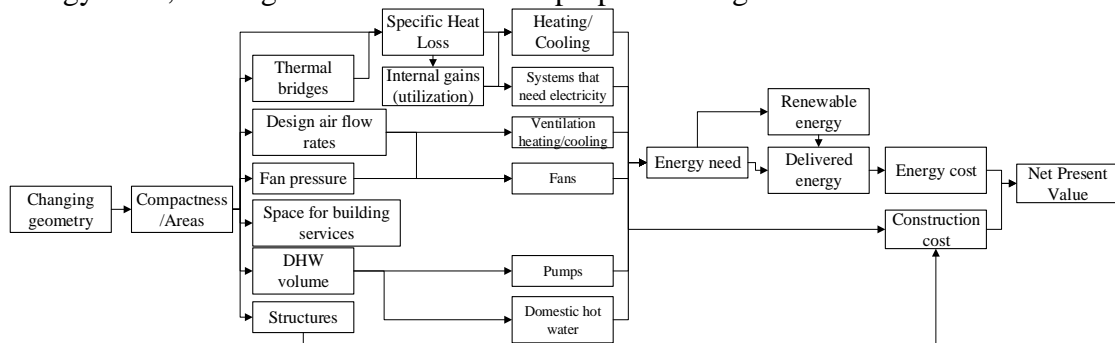


Figure 4. Impact network caused by changing the building geometry.

Table 1 connects design functions and parameters identified in the hierarchical decomposition of the NPV to the design tasks listed in Appendix 1 by using task

numbers. Design tasks listed in the Appendix only cover the current design process up to the energy certification calculation. Therefore, rows 9 and 10 in Table 1 have no corresponding tasks because of no clear consideration of construction costs and/or life-cycle costs in a typical design office today. However, according to energy efficiency research community (Kurnitski and Group, 2013) and European Union energy efficiency directives and methodologies, investment costs and life-cycle costs are the major aspects for rationalizing energy efficient building design (Council, 2012). Certainly, these are not the only criteria (Arroyo, Tommelein and Ballard, 2012). Table 1 indicates how late changes in the building geometry influence other design disciplines. Comparing the tasks in Table 1 to the task sequence in Figures 3 and 4, we can see that the changing geometry means a large amount of rework, as everything must be reconsidered.

*Table 1. Connecting system design parameters to design tasks and disciplines.*

Nr	Design Parameters and Functions	Task Numbers	Discipline	Stage
1	Compactness, Areas	3, 8		Schema
2	Space required for HVAC/MEP systems	6	Architect	tic
3	Structures	7		Design
5	Thermal bridges, design air flow rates, fan pressure, specific heat loss and internal gains	14, 15, 21, 26	Building Services Engineer	Preliminary
6	All systems design: heating, cooling, ventilation heating and cooling, pumps and domestic hot water	All tasks of BSE	Electrical Engineer	Design
7	Electricity and automation systems	All tasks of BSE	Building Services Engineer	
8	Energy need, renewable energy, delivered energy, energy cost	34	Contractor/Cost surveyor	-
9	Construction cost	Not a design task	Building Services Engineer	-
10	Net present value	Not a design task		

## DISCUSSION

Current broken management methods have not helped to reduce complexity, rather they have increased it. In the literature review and visualization of the existing processes (tasks) and the energy efficiency calculations (design parameters) in Table 1, we showed how the product, processes and organization are interrelated above these three domains. Due to the inductive nature of design, it involves complexity, and it needs to be reduced or managed better. To achieve that, existing and perhaps new methods are needed. We are revisiting here existing solutions, technological and organizational means to reduce or in some instances to manage complexity.

### REDUCTION OF PRODUCT COMPLEXITY

Building information modelling (Eastman, et al., 2011) has fundamentally changed the way we represent the functional and physical characteristics of a building in digital form. In historical terms, it has moved from static and illustrative drawings to highly functional and mathematical models that can be used for various kinds of simulations that support design processes and specific tasks, e.g., design coordination through clash detection. Building information modelling can also be used for developing a common language in a project team as it helps to visualize the building in one unified way (3D), understandable to everybody (Alarcon, Mandujano, and Mourgues, 2013).

As in the Toyota (Morgan and Liker, 2006), rapid prototyping (3D printing) could be used for experimenting and studying the different design solutions. This is especially important in the early stages of design (Pennanen and Koskela, 2005). Physical mock-ups/prototypes were largely used in the early years of engineering, especially in the bridge construction (Kranakis, 1997). The 3D printed models can be used for studying their functional characteristics under specified conditions, common to experimental sciences (Godfrey-Smith, 2009).

### **REDUCTION OF PROCESS AND ORGANIZATION COMPLEXITY**

Lean construction (Koskela, 2000), integrative design (Reed, 2009) and/or integrated project delivery (IPD) are examples of reducing process complexity, not only in process terms, but also in terms of organization. These could be viewed as process models that aim to reduce the non-value adding tasks or remove these from the system (Koskela, 2000). Secondly, these approaches break the long communication chains and through colocation, information sharing and communication on design alternatives and solutions is more direct “Knots” can be designed into a process, which contains coupled decisions and tasks (Dave, et al., 2015). This means that design alternatives on different levels of resolutions or decomposition can be internally verified within a project team and validated with the client. Extreme collaboration (Chachere, Kunz and Levitt, 2003) and “Obeya room” (Morgan and Liker, 2006), “Big Room” in lean construction terminology are the methods often used for reducing process and organizational complexity.

### **CONCLUSIONS**

It is evident that most important decisions are made in the early stages of the design process because architect’s work influences all the other disciplines. Designing is complex, not only because of complexity within one domain, but because of interdependencies above all three domains: product, process and organization. In this research, we have used the DSM and hierarchical decomposition of the NPV for visualizing the interdependency of design tasks and disciplines and how changes propagate throughout the system. Current design of energy efficient buildings is a linear and one-shot approach without iterations planned into the process. Broken management techniques do not help to reduce the complexity, but lean construction practices together with BIM and other new technologies could be used in managing the design complexity. Regarding buildings as a complex system emphasizes the need for understanding interdependencies in design and the impact of the design changes on the lifecycle costs. New methodologies and technologies discussed above could be used to visualize the impact of design changes to be linked to client’s requirements and lifecycle costs.

### **REFERENCES**

- Alarcon, L. F., Mandujano, M. G. and Mourgues, C. 2013. Analysis of the implementation of VDC from a lean perspective: Literature review. In: *Proc. 21<sup>st</sup> Ann. Conf. of the Int’l. Group for Lean Construction*. Fortaleza, Brazil, Aug 31-2.



- Arroyo, P., Tommelein, I. D. and Ballard, G. 2012. Deciding a sustainable alternative by ‘choosing by advantages’ in the AEC industry. In: *Proc. 20<sup>th</sup> Ann. Conf. of the Int’l. Group for Lean Construction*. San Diego, USA, July 18-20.
- Ballard, G. 2000. Positive vs negative iteration in design. In: *Proc. 8<sup>th</sup> Ann. Conf. of the Int’l. Group for Lean Construction*. Brighton, UK, July 17-19.
- Ballard, G. and Koskela, L. 1998. On the agenda of design management research. In: *Proc. 6<sup>st</sup> Ann. Conf. of the Int’l. Group for Lean Construction*. Guarujá, Brazil, Aug 13-15.
- Bertelsen, S. and Emmitt, S. 2005. The client as a complex system. In: *Proc. 13<sup>th</sup> Ann. Conf. of the Int’l. Group for Lean Construction*. Sydney, Australia, July 19-21.
- Bertelsen, S. 2003a. Complexity - A new way of understanding construction. In: *Proc. 11<sup>th</sup> Ann. Conf. of the Int’l. Group for Lean Construction*. Blacksburg, Virginia, Jul. 22-24.
- Bertelsen, S. 2003b. Construction as a complex system. In: *Proc. 11<sup>th</sup> Ann. Conf. of the Int’l. Group for Lean Construction*. Blacksburg, Virginia, Jul. 22-24.
- Chachere, J., Kunz, J. and Levitt, R. 2003. *Can you accelerate your project using extreme collaboration? A model based analysis*. Stanford, CA: Stanford University, Center for Integrated Facility Engineering (CIFE).
- Council, 2012. *Commission Delegated Regulation (EU) No 244/2012* of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. Brussels: Official Journal L 81, 21/3/2012, pp. 18–36.
- Dave, B., Pikas, E., Kerosuo, H. and Mäki, T. 2015. ViBR—Conceptualising a virtual big room through the framework of people, processes, and technology. *Procedia Economics and Finance*, 21, pp.586–593.
- Eastman, C., Teicholz, P., Sacks, R. and Liston, K. 2011. *BIM handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractors*. New Jersey: John Wiley & Sons.
- Estonian Centre for Standardization 2012. *EVS 811: 2012 Building design*. Tallinn, Estonia.
- Eppinger, S. D. 1991. Model-based approaches to managing concurrent engineering. *Journal of Engineering Design*, 2(4), pp.283-290.
- Godfrey-Smith, P. 2009. *Theory and reality: An introduction to the philosophy of science*. Chicago: University of Chicago Press.
- Howell, G. A., Ballard, G. and Tommelein, I. 2010. Construction engineering—Reinvigorating the discipline. *Journal of Construction Engineering and Management*, 137(10), pp.740-744.
- Koskela, L., Huovila, P. and Leinonen, J. 2002. Design management in building construction: from theory to practice. *Journal of Construction Research*, 3 (01), pp.1-16.
- Koskela, L. 2000. *An exploration towards a production theory and its application to construction*. PhD. VTT Technical Research Centre of Finland.
- Kranakis, E. 1997. *Constructing a Bridge: An Exploration of Engineering Culture, Design, and Research in Nineteenth-Century France and America*. Cambridge: Massachusetts Institute of Technology Press.

- Kurnitski, J. 2013. *REHVA nZEB technical definition and system boundaries for nearly zero energy buildings*. Brussels, Belgium: Federation of European Heating, Ventilation and Air conditioning Associations.
- Lee, T. 2003. *Complexity theory in axiomatic design*. Ph.D. Massachusetts Institute of Technology.
- Morgan, J. M. and Liker, J. K. 2006. *The Toyota product development system*. New York, US: Taylor & Francis.
- Government Office 2012. VV No 268: 2012 Estonian Government ordinance No 68, 2012 *Energiatõhususe miinimumnõuded*. (30.08.2012); RT I, 05.09.2012, 4.
- Pennanen, A. and Koskela, L. 2005. Necessary and unnecessary complexity in construction. In: *Proc. of 1<sup>st</sup> Int'l. Conf. on Built Environment Complexity*. University of Liverpool, Liverpool, UK, September.
- Pikas, E., Kurnitski, J., Liias, R. and Thalfeldt, M. 2015. Quantification of economic benefits of renovation of apartment buildings as a basis for cost optimal 2030 energy efficiency strategies. *Energy and Buildings*, 86, pp.151-160.
- Pikas, E., Thalfeldt, M. and Kurnitski, J. 2014. Cost optimal and nearly zero energy building solutions for office buildings. *Energy and Buildings*, 74, pp.30-42.
- Reed, B. 2009. *The integrative design guide to green building: Redefining the practice of sustainability*. New Jersey: John Wiley & Sons,
- Snowden, D. J. and Boone, M. E. 2007. A leader's framework for decision making. *Harvard Business Review*, 85(11), pp.1-9.
- Steward, D. V. 1981. *Systems analysis and management: structure, strategy, and design*. New York: Petrocelli Books.
- Suh, N. P. 2001. *Axiomatic design: Advances and applications*. New York: Oxford University press.
- Tommelein, I. D. 2015. Journey toward lean construction: Pursuing a paradigm shift in the AEC Industry. *Journal of Construction Engineering and Management*, 141(6), pp.1-12.
- Wynn, D. C. 2007. *Model-based approaches to support process improvement in complex product development*. PhD. University of Cambridge.