WORKING TOGETHER IN A KNOT: THE SIMULTANEITY AND PULSATION OF COLLABORATION IN AN EARLY PHASE OF BUILDING DESIGN

Jenni Korpela[1] and Hannele Kerosuo

[1] *Institute of Behavioural Sciences, CRADLE, University of Helsinki, Finland*

Construction projects are complex, and many open questions arise in the early phases of projects. Turning these questions into realistic requirements is a critical task that demands a good deal of specific information, multiple types of expertise and collaboration between designers. Knotworking is a new way to work as a group for a short period of time to accomplish a critical task in a BIM-based building process. This study focuses on the experimentation with knotworking in an early stage of a building project. A characteristic of knotworking is that continuity is connected to the object of the work at hand, not to the stability of the team. An object of activity is considered as a basic motive and purpose of human activity. The object of the design activity is here a school-community centre in central Finland. According to activity theory, an idea or a concept needs to be experimented with to become a new practice. Over a two-day session, two interdisciplinary teams of participants created alternative design solutions and evaluated them. The teams included an architect, a cost calculator, a structural engineer, a HVAC designer, a coordinator, a visualizer and a developer, and an energy specialist. The data consist of video-recordings and observations of these sessions. During the knotworking session, the participants were able to receive feedback from other design disciplines and stakeholders. Knotworking made the simultaneous exchange of information and sharing of expertise possible. Quick changes between working individually, in pairs, in small groups or in the whole group characterize the pulsating quality of working in a knot. With enabling technology and a new kind of pulsating collaboration, knotworking supports 1) creating concrete design solutions in a short period of time, 2) increasing designers' knowledge of the implications of their decisions on the work of their colleagues and the quality of design, and 3) easing shifts from coordinative talk to collaborative design and back.

Keywords: collaboration, building design, knotworking, pulsation, activity theory.

INTRODUCTION

Construction projects are complex, and the early phases of projects contain many open questions. Turning these questions into realistic requirements is a critical task that calls for a good deal of specific information, multiple types of expertise and close collaboration. Schade and colleagues (2011) describe the early design phase as the point at which decisions with a significant effect on the final costs are made. As a consequence, designers should be more involved in producing different solutions and realistic options for clients to choose among. However, conceptual design is shown as

[1] jenni.korpela@helsinki.fi

Korpela, J and Kerosuo, H (2014) Working together in a knot: The simultaneity and pulsation of collaboration in an early phase of building design *In:* Raiden, A B and Aboagye-Nimo, E (Eds) *Procs 30th Annual ARCOM Conference,* 1-3 September 2014, Portsmouth, UK, Association of Researchers in Construction Management, 865-874.

a time-consuming process, in which design disciplines carry out their design and analyses separately, and the number of possible iterations is low (Flager and Haymaker 2009, Flager *et al*. 2009, Eastman 2011).

New technologies, such as building information modelling (BIM), BIM platforms, cloud computing and mobile devices, may have the potential to increase collaboration between the different parties of a construction process (Volk *et al*. 2014, Succar 2009, Singh *et al*. 2011). According to Eastman and colleagues (2011), BIM tools enable designers to receive *"almost real-time"* feedback from each other.

However, BIM alone does not improve collaboration across professional communities (Neff *et al*. 2010). Besides new technology, knowledge on information sharing is an important facet of collaboration (Pikas *et al*. 2013). In design meetings, designers try to find or replace missing information by making assumptions, promising to verify information between meetings when this task is easily forgotten, or by searching for the information during the meeting, which takes valuable time and distracts other designers (Koskela *et al*. 2002).

Complex design problems in the building process require designers and specialists to work together to solve specific problems in a temporary team (Dossick and Neff 2011). Kvan (2000) suggests that design collaboration is a more demanding activity than completing a project as a team, as it 'requires a higher sense of working together'. According to van Gassel (2014), to enhance collaborative actions in design, participants should have the proper tools to explain their thoughts and have 'a common language' to understand each other.

Knotworking is a new way of working together as a group to solve critical tasks in a building process (Kerosuo *et al*. 2013). It is a flexible collaboration method for mastering unstable objects and fragmented processes in pursuing intersecting activities. Knotworking is characterized as 'a pulsating movement of tying, untying and retying together seemingly separate threads of activity' (Engeström 2008: 194). However, it is not clear what pulsation means in construction processes.

The focus of this study is on the forms of design collaboration in knotworking. How does the collaboration between project participants and design specialists take place during knotworking? Does knotworking enable an effective way of working together in a building project? The case studied here is the design of a school-community centre in an early stage of a building project. Over a two-day session, two interdisciplinary teams of participants created alternative design solutions and evaluated them. The case was part of the development of knotworking that took place in the Built Environment Process Re-engineering (PRE) research programme.[2] The idea of knotworking was tested in three real building projects in the programme, the first of them being the focus of this study.

Developed in healthcare activities, knotworking has not previously been applied as a collaboration method in construction. We begin our paper with an introduction of the knotworking concept. Then we describe the data and the methods of the study. After that, we present and discuss the results of the analysis, and finally, we conclude the paper with suggestions for further research. The study deepens knowledge on social forms of collaboration early in the design process.

[2] The PRE programme is part of the Strategic Centre for Science, Technology and Innovation of Built Environment Innovations RYM Oy, http://www.rym.fi/en/programs/builtenvironmentprocessreengineeringpre/.

KNOTWORKING IN THE EARLY DESIGN PHASE

Knotworking is a new form of collaborating during critical phases of a building project. It was initiated as a form of organizing and performing work activity in connection to co-configuration models of production, and it represents 'the emerging interactional core of co-configuration' (Engeström 2008: 195). Engeström argues that the nature of teams depends on the historical type of production within which they are implemented (p.190). Knotworking resembles teamwork, but knots are less stable than teams. Knots are task-dependent constellations formed on a temporary basis. They are more related to the requirements of the work processes on the level of practices, and the development of knotworking is closely tied to practical experiments and the testing of different project-based tasks.

BIM is considered 'an emerging technological and procedural shift' within the construction industry (Succar 2009: 357). BIM enables project partners to be connected more tightly than before through technology, but at the same time they still remain organizationally divided, often lacking timely access to crucial information (Dossick and Neff 2010). The need to develop methods of crossing organizational boundaries and task divisions in a new way is a developmental challenge in BIM-based design contexts. Poor communication, ambiguous requirements and regular misunderstandings often cause delays in the industry (Forbes and Ahmed 2011, Neff *et al*. 2010). The combination of contributors is usually constantly changing during a building project. The coordination of the various contributions and collaboration between participants is based on contractual agreements, rules, the formal division of labour, and routine practices (Hardin 2009, Bishop *et al*. 2009).

New methods organizing project work, for instance, in 'Big Rooms', have been developed along with the implementation of BIM to solve the collaboration problems in the construction industry. Knotworking resembles Big Rooms in that designers work side by side in the same place to share information with each other more effectively than if they were working separately in different design offices (Kanzode and Reed 2008). The Big Room is best suited for large projects in which designers are employed in one project full time. Most construction projects are usually smaller in Finland, and designers may work in parallel on several projects in different parts of Finland. Working together in the same premises may then become a challenge that cannot easily be organized.

In this article, we focus especially on the aspects of design actions and interactions in knotworking. Interaction and communication have been the focus of many studies in construction, but what is often missing is their connection to the object of their work activity. Characteristic of knotworking is that the social interaction is connected to the object of work at hand, not to the interaction or communication between designers as such. The object of activity is here understood in its activity-theoretical meaning (Engeström 2008: 88-89) as a purposeful, shared target of the designers' actions and interactions in the design activity. The object of activity can be understood as material as well as ideal. However, it is not easy for designers to work on a shared object because they often have very different aims and commitments in construction projects (Bishop *et al*. 2009). Learning challenges emerge as participants develop new ways of working and stimulate change both in the participants and their organizations (Fenwick 2007). Organizational learning takes place when participants whose relationships are loose solve complex problems driven by internal motivation (Blackler and McDonald 2000). In this study, the object of the design activity is a

school-community centre in central Finland. The participants solved the learning challenges by developing new tools and social forms of collaboration.

THE DATA AND THE METHODS OF THE STUDY

The data were gathered in the knotworking experiment, which was carried out in the early phase of design. The designers and construction professionals developed the concept of knotworking with the help of the researchers (Kerosuo *et al*. 2013). The participants decided to test knotworking in central Finland, where a city had planned for a school community centre to be built. The knotworking experiment was funded by the PRE research programme. Before engaging in the experiment, the participants met five times in total to plan the experiment. The plan included the list of the participants in the two temporary teams (i.e., knots), the aims of the design work, the initial data, the schedule of the experiment and its working methods, the design and assessment tools, and the collaboration with the client and the end users.

The object of the first team was to create different design alternatives for a new school-community centre on an empty building site (*"Team New"* in the analysis). The second team produced renovation alternatives for an old listed building (named *"Team Renovation"*). Team New included an architect, a cost analyst, a HVAC designer, an energy specialist (who did energy and temperature simulations), a structural designer, a developer, a coordinator (who acted as the leader of the team) and a visualizer (whose task was to create an instrument for comparing the design alternatives of the knot). Team Renovation consisted of two architects, a cost analyser, a HVAC designer, an energy specialist, a structural designer, a coordinator and a visualizer, who also acted as a developer. Both teams had access to the same initial data, the contents of which were the initial options for the models produced by an architect, the client's requirements and the end users' wishes for the school-community centre.

The data consist of recordings of the two teams working in two-day knotworking sessions. The knotworking sessions were video-recorded and attended by the researchers. Team New worked 8 hours and 35 minutes and Team Renovation worked 7 hours and 30 minutes during the two-day knotworking session. Five researchers from three different research institutes observed Team New and four researchers observed Team Renovation.

In a first phase of the analysis, the course of the knotworking sessions was strictly classified into collaborative work, individual work and preparation for the presentation of results to the client and the users of the school community centre. In the second phase, every participant's tasks and actions were listed on an Excel sheet in five-minute time slots with the help of the recordings. A five-minute time slot was chosen for the empirical unit of analysis because it was long enough to contain a meaningful conversation but short enough to identify single events in the knotworking. However, it soon became clear that the strict division between collaborative and individual work gave a very simplified picture of what was taking place during the knotworking sessions. It seemed that the designers were simultaneously engaged in collaborative and individual work as well as in working in pairs and groups.

In the third phase of the analysis, the forms of the participants' collaboration during the knotworking session were identified. The form of collaboration was marked for each participant in each five-minute time slot. The forms of collaboration were

individual working, working in pairs, working in a group (here defined as a group of 3–7 persons, more than a pair, less than a whole team), and the whole team working together. In addition to these, the group 'other' was added to include work that was not related to the design tasks at hand. The participants' absences from the session, for instance, going to the toilet, were also included in this group.

THE FORMS OF COLLABORATION

Figure 1 below shows the distribution of the individual work and the different forms of collaboration in both teams. The shares are percentages of the total working hours of the two-day knotworking session. Most of the time both teams worked in groups (36% for Team New and 41% for Team Renovation). Typically, the groups dealt with one topic 5–15 minutes at a time. It was also typical that the participants in a group might change during a conversation. The second largest form of collaboration was individual working, which might include asking short questions or providing answers to the others, although the participant's main focus was on his or her own work. Team New spent about 16% of their time working both in pairs and as a whole team. Team Renovation spent the least time working in pairs. During the pair working, two members of the team worked on the same topic, side-by-side, commenting on and discussing each other's work. When working as a whole team, everyone listened and followed the presentation on the screen unless they were not actively participating in the discussion. In addition to these collaboration forms, the class 'other' describes absences and work that was not included in the knotworking.

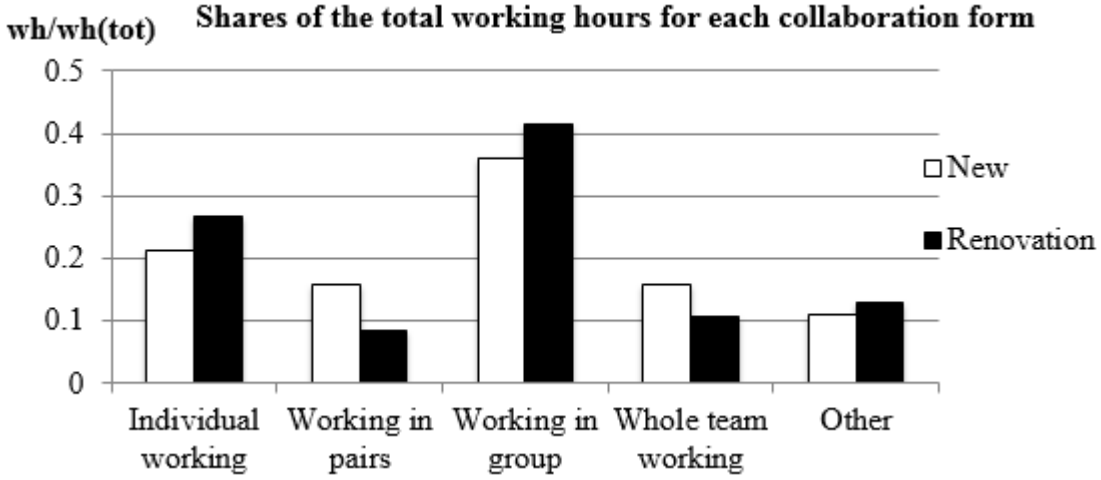

Figure 3 Shares of the total working hours for the individual work and each collaboration form.

Figure 2 shows the distribution of the individual work and the different collaboration forms for each member in both teams. The distributions between the two teams have similarities and differences. In Team New, the cost analyst and the architect did the most of the individual work. In Team Renovation, the energy specialist and the cost analyst worked by themselves the most. In Team New, the energy specialist worked the most in a pair and with the HVAC designer the most. In Team Renovation, the architects worked as a pair the most.

In both teams, the coordinator and the visualizer actively worked in groups. In Team New, the structural designer also spent much time working in groups, as well as the second architect in Team Renovation. In the next section, we present examples of how the forms of collaboration shifted between topics and tasks.

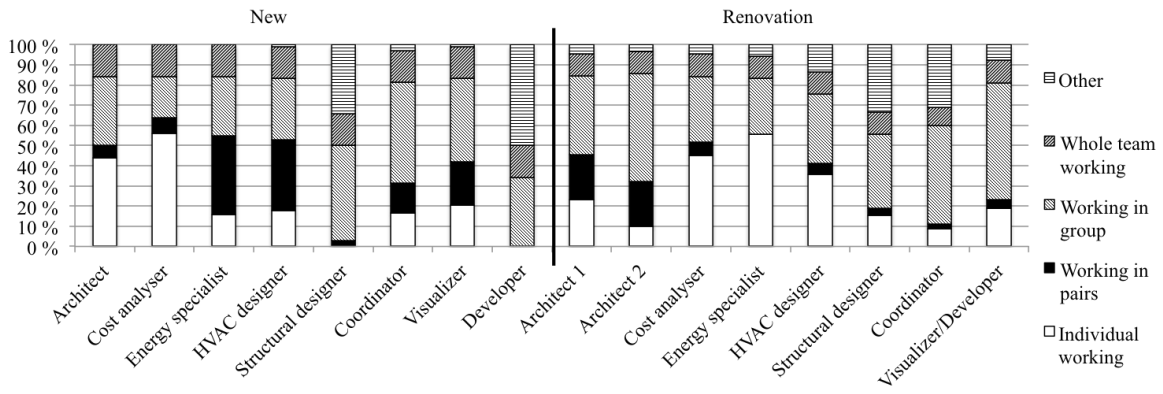

Figure 4 Individual work and the collaboration forms of each participant in the knots.

EXAMPLES OF SIMULTANEITY AND PULSATION IN THE DESIGN COLLABORATION

In this section, we present examples of the diverse forms of working and collaboration that occurred during the knotworking sessions. How did working together proceed during the knotworking? Our aim is to illustrate the specific features of simultaneity and pulsation in knotworking. Two of the examples focus on the most discussed topics in each team: an overheating issue discussed by Team New and the old building and its limits discussed by Team Renovation. The third example focuses on Team New trying to improve the methods and tools of their work in the knot. The tables (1, 2 and 3) show the collaboration forms that occurred during the handling of each topic.

Table 2 Variation of the forms of collaboration during the handling of the overheating issue, Team New. (I) for individual working, (Pa) for pair working, (Gr) for group working, (Wh) whole team working, (O) other.

Time	Arch.	Cost a.	Energy	HVAC	Coord.	Vis.	Struct.	Dev.
4:20:00	I	I	Pa1	Pa1	Pa2	Pa2	O	O
↓	I	I	Gr	Gr	Gr	Gr	Gr	O
↓	I	I	Gr	Gr	I	I	O	O
↓	Gr	Gr	Gr	Gr	Pa2	Pa2	Gr	Gr
↓	Gr	I	Gr	Gr	Gr	Gr	Gr	Gr
↓	Wh	Wh	Wh	Wh	Wh	Wh	Wh	Wh
↓	Gr	I	Gr	Gr	Gr	Gr	Gr	Gr
↓	Gr	I	Gr	Gr	I	I	Gr	Gr
5:30:00	Wh	Wh	Wh	Wh	Wh	Wh	Wh	Wh

The biggest issue for Team New was the overheating problem in a few rooms of the building (see Table 1). The problem became urgent when the HVAC designer and the energy specialist calculated the periods of the facility use. It turned out that the temperature in some rooms was estimated too high. They asked the cost analyst to calculate the costs of a larger AC device. The HVAC designer asked the architect whether they had solved similar problems in previous cases. Meanwhile, the coordinator and the visualizer simultaneously listened to the conversation and worked on another task. The architect showed his modelled plan, and the group speculated whether switching the spaces to another cardinal point would solve the problem. The

coordinator pointed out that most of the temperature load came from the estimated number of children in the rooms. The estimation was considered unrealistically high, because due to the school holidays, most of the children would not be in the facility. At this point, the cost analyst had finished his calculations for the new AC device. The team decided that it was up to the client to adjust to the lower temperature requirements during the summer season or to order a larger and more expensive air conditioner.

The placement of new spaces in the old building was a big issue for Team Renovation (Table 2). The discussion on this topic started when the structural designer commented on the insulating wall to the cost analyst and the researchers. The architects, the HVAC designer and the energy specialist discussed the architects' first design option and its plant room, while the structural designer made some calculations about the insulation. The coordinator came back to the premises after speaking with one of the villagers. He shared some additional information about the old building with the others. The structural designer shared his calculations concerning insulation thickness in the walls. The architect made a quick sketch placing all the spaces inside the old building, and the group discussed whether they should continue exploring that option, even if it did not fulfil all the requirements. They decided to give it a try; it would be an interesting and a different solution.

Table 3 Variation of the forms of collaboration during the discussion about the old building and its limits, Team Renovation. (I) for individual working, (Pa) for pair working, (Gr) for group working, (Wh) whole team working, (O) other.

Time	Arch.	Arch. 2	Cost a.	Energy	HVAC	Coord.	Vis.	Struct.
1:35:00	Pa	Pa	Gr1	I	I	O	I	Gr1
↓	Gr2	Gr2	I	Gr2	I	O	Gr1	Gr1
↓	Gr2	Gr2	I	Gr2	Gr2	O	Gr2	I
↓	Gr1	Gr1	I	Gr1	I	Gr1	Gr1	Gr1
↓	O	I	Gr1	Gr1	I	Gr1	Gr1	Gr1
↓	Gr1	Gr1	Gr1	I	I	Gr1	Gr1	Gr1
2:05:00	Gr1	Gr1	Gr1	Gr1	I	Gr1	Gr1	Gr1

The third example illustrates Team New's attempt to improve their tools and methods of working (Table 3). Team New tried to improve their working methods by implementing Dropbox and trying to unify their space classifications. The coordinator inquired about the classifications that the cost analyst was using in his software. He said that the classification in use was based on energy analysis software, but the cost analyst could also use area information from the architect as a shortcut in his work. He then stopped the discussion in order to ask the HVAC designer about the number of AC devices. The coordinator wanted to try a unifying space classification and the space types used in a different software program. The HVAC designer explained how they combined the architect's space object information with their own classification and gave an Excel sheet containing this mapping to the coordinator. They decided to install Dropbox software to ease the file exchange in the knot. The coordinator helped the architect, the cost analyst and the structural designer to install Dropbox, and the developer reminded the others about the schedule of the day. The energy specialist and HVAC designer continued discussing the E value, and the coordinator started working on the classifications. Later in the afternoon they returned to the

classification topic. The architect shared what kind of classification his software uses. The group concluded that the software should be developed in such a way that the name, number and type of space could be easily transferred to another software program used by other designers.

Table 4 Variation of the forms of collaboration during the discussion on improving the tools in use, Team New. (I) for individual working, (Pa) for pair working, (Gr) for group working, (Wh) whole team working, (O) other.

Time	Arch.	Cost a.	Energy	HVAC	Coord.	Vis.	Struct.	Dev.
2:00:00	Gr	Gr	Gr	Gr	Gr	Gr	Gr	O
↓	Gr	Pa	I	Pa	Gr	Gr	Gr	O
↓	Gr	Gr	I	Gr	Gr	Gr	Gr	O
↓	I	I	I	Gr	Gr	Gr	O	O
↓	Gr	I	Pa2	Pa2	Gr	Gr	Gr	Gr
2:30:00	Gr	Gr	Pa2	Pa2	Gr	I	Gr	O
↓	Break in topic, other discussion and working. Continuing after 1 hour.							
3:20:00	Gr	Gr	Pa2	Pa2	Gr	Gr	O	Gr
3:30:00	Gr	I	Pa2	Pa2	Gr	Gr	Gr	Gr

DISCUSSION

In this chapter, the nature of simultaneity and pulsation is clarified in knotworking. Throughout almost the whole observation period, the representatives of different design disciplines worked simultaneously on different design problems. As examples 1 and 2 show, the simultaneity of conducting design tasks gave the participants an opportunity to quickly test alternative designs and recognize poor design solutions. Rather than just validating a chosen design alternative (Flager *et al*. 2009), the participants were able to run multiple simulations and exploit the results in improved design solutions. The *"almost real-time"* feedback suggested by Eastman and colleagues (2011) succeeded during knotworking, as seen in example 1, in which the cost analyst provided calculations in less than hour for the rest of the team to evaluate.

The pulsating nature of knotworking is especially explicated in example 3, where the team is trying to create a new classification system. The classification system remains an object of activity (Engeström 2008: 88-89), but the members of the group vary in their focus by engaging, disengaging and re-engaging themselves in the topic. The core of the discussion pulsated and bounced among the members of the group, depending on which part of the classification system was being studied.

After the knotworking session, the participants felt that working together increased their understanding of the purposes and goals of the other disciplines (cp. Kvan 2000, van Gassel 2014). The team learned about each other's methods of working and tool use as well as the limitations of their methods and tools.

> You knew what another [designer] was doing. You knew what costs were taken into account, why did the HVAC designer choose those devices, why does the architect do that and that. Seldom in a project do you get the possibility to clarify the goals and purposes of others so fast. (The visualizer/developer)

The participants thought that the knotworking could be developed as a method for creating an expanded project design. Normally, creating a project design is an extensive process that happens over a long time span. Exploring multiple design solutions in a short time would also be beneficial for the client.

CONCLUSIONS

The simultaneous and pulsating quality of working in knots benefited the early phase of design in three ways. First, it supported the creation of concrete design solutions in a short period of time. The knotworking enabled the design teams to create concrete design solutions and solve problems in few hours that normally would take days to resolve. The results created in the knots were actual design solutions and documents, making them more productive than a usual design meeting. Working in the same place and exchanging information helped the designers to create better options more productively than designing on their own. Options were easily tested and accepted or rejected as a result of the immediate discussion.

Second, knotworking increased the designers' knowledge of the implications of their decisions on the work of their colleagues and the quality of design. It made other designer's choices visible to others and thus increased a common understanding about the other designer's solutions.

Third, knotworking eased shifts from coordinative talk to collaborative design and back. The design teams worked simultaneously and shifted easily from one form of collaboration to another. During the knotwork session, the teams worked mostly in groups, but were also able to work in pairs and individually. All forms of working served their purpose, from individual or pair work to accomplish specific design tasks to groups or the whole team focusing on more general problem solving and developing their work. The forms of collaboration varied even during the handling of one topic. Moving from one topic to another, as well as between collaboration forms, was fluent. The participants could easily take a break from their own work to take part in an on-going discussion and then continue working on their original task.

Knotworking appears to be an effective way to produce design options for early design phases. To implement knotworking in other design phases requires further research and development. The object of activity must be defined and developed together with the participants in each knot.

REFERENCES

Blackler, F and McDonald, S (2000) Power, mastery and organisational learning, *"Journal of Management Studies"*, **37**(6), 832-51.

Bishop, D ,Felstead, A, Fuller, A, Jewson, N, Unwin, L and Kakavelakis, K (2009) Constructing learning: adversarial and collaborative working in the British construcion industry. *"Journal of Education and Work"*, **22**(4), 243-260.

Dossick, C S and Neff, G (2011) Messy talk and clean technology: communication, problem-solving and collaboration using Building Information Modelling. *"Engineering Project Organizational Journal"*, **1**(2), 83-93.

Dossick C S and Neff G (2010) Organizational divisions in BIM-enabled commercial construction. *"Journal of Construction Engineering and Management"*, **136**(4), 459–67.

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 and Sons, Inc.

Engeström, Y (2008) *"From teams to knots: Activity-theoretical studies of collaboration and learning at work"*. Cambridge: Cambridge University Press.

Fenwick, T (2007) Organisational learning in the *"knots"*. Discursive capacities emerging in a school-university collaboration. *"Journal of Educational Administration"*, **45**(2), 138-153.

Flager, F and Haymaker J (2009) A Comparison of Multidisciplinary Design, Analysis and Optimization Processes in the Building Construction and Aerospace. CIFE Technical Report #TR188. Stanford University.

Flager F, Welle B, Bansal P, Soremekun G and Haymaker J (2009) Multidisciplinary process integration and design optimization of a classroom building, *"Journal of Information Technology in Construction"*, **14**, 595-612.

Forbes, H L and Ahmed, S M (2011) *"Modern Construction – Lean Project Delivery and Integrated Practices"*. New York: CRC Press.

Van Gassel, F J M, Láscaris-Comneno, T and Maas, G J (2014) The conditions for successful automated collaboration in construction. *"Automation in Construction"*, **39**, 85-92.

Hardin, B (2009) *"BIM and construction management: Proven tools, methods and workflows"*. Indiana, US: Widey Publishing.

Kanzode, A and Reed, D (2008) A practitioner's Guide to Virtual Design and Construction (3D/4D) Tools on Commercial Projects: Case Study of a Large Healthcare Project. In W. Kymmel (ed.) *"Building Information Modeling. planning and managing construction projects with 4D CAD and simulations"*. New York: McGrawHill.

Kerosuo, H, Mäki, T and Korpela, J (2013) Knotworking – A novel BIM-based collaboration practice in building design projects. In *"Proceedings of the 5th International Conference on Construction Engineering and Project Management, 2013"* 9-11 January 2013, Orange County, California. ,

Koskela, L, Huovila, P and Leinonen, J (2002) Design management in building construction from theory to practice. *"Journal of Construction Research"* **3**(1), 1-16.

Kvan T (2000) Collaborative design: what is it? *"Automation in Construction"*, **9**(4), 400-415.

Neff, G, Fiore-Silfast, B and Dossick, C S (2010) A case study of the failure of digital communication to cross knowledge boundaries in virtual construction. *"Information, Communication and Society"*, **13**(4), 556- 573.

Pikas, E, Sacks, R, and Hazzan, O (2013) Building Information Modeling education for Construction Engineering and Management. II: Procedures and Implementation Case Study. *"Journal of Construction Engineering Management"*, 139(11), 05013002. Case Studies.

Schade, J, Olofsson, T and Schreyer, M (2011) Decision-making in a model-based design process. *"Construction Management and Economics"*, **29**(4), 371-382.

Singh, V, Gu, N, Wang, X (2011) A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *"Automation in Construction"*, **20**, 134-144.

Succar, B (2009) Building information modeling framework: A research and delivery foundation for industry stakeholders. *"Automation in Construction"*, **18**, 357-375.

Volk, R, Strengel, J and Schulmann, F (2014) Building information modeling (BIM) for existing buildings – Literature review and future needs. *"Automation in Construction"*, **38**, 109-127.