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Level of sub-contracting design responsibilities in design and construct civil engineering bridge projects

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Abstract

Purpose – In the construction industry, an under researched area of study is how main contractor (MC) sub-contract design responsibilities to sub-contractor (SC). This lack of knowledge is particularly serious in the context of delivery methods such as design and construct where design responsibilities are pushed down the supply chain. In this study, it is aimed to explore which level of design responsibility MCs sub-contract to SCs, for what reasons, and what the impact of sub-contracting decisions is on projects.

Design/methodology/approach – A qualitative in-depth multiple case study was conducted. Six sub-contracting cases were examined in two civil engineering projects. In each project, the MCs sub-contracted pre-fabricated beams, reinforcement and railing to SCs. Data collection included document analysis and interviews. A within-case and cross-case analysis was conducted to examine emerging empirical patterns. These patterns were used to elaborate theory and develop propositions.

Findings – MCs sub-contracted design responsibilities to SCs as suggested by literature. However, despite that sub-contracting was in keeping with literature, several problems were reported in the cases where MCs involved SCs no earlier than in the construction stage. This is not to be expected according to theory.

Originality/value – This study adds value to the sub-contracting field as it provides new insights in relationships between the level of design responsibilities sub-contracted and the impact of that on projects. The study also revealed new factors such as building information modelling (BIM) interoperability that should get more attention in sub-contracting.

Keywords Sub-contracting, Design responsibility, Civil engineering, Supply chain, Construction management, Design and construct

Paper type Research paper

Introduction

In the construction industry, clients have always tried to make effective use of knowledge and skills available on the market. In the past two decades, this has resulted in responsibilities being transferred from the client to the contractor, and contracts that make the contractor responsible not only for construction, but also for design. Examples of such contracts are engineering and construct (E&C), design and construct (D&C), design, build, finance, maintain (DBFM) and similar types (Makkinga *et al.*, 2018; Winch, 2010). For the client, such contracts are beneficial as tasks and risks become the responsibility of the contractor.

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In addition, the specific knowledge and skills of the contractor can be used, leading to a more efficient and effective production process.

However, the changes in design responsibilities not only affect the relationship between client and main contractor (MC), but also between the MC and sub-contractor (SC)/suppliers further down the supply chain. The reason is that in the construction industry, MCs sub-contract sometimes up to 90% of the work to their SCs (Chiang, 2009; Hinze and Tracey, 1994; Tan *et al.*, 2017; Vrijhoef and Koskela, 2000). SCs can supply workers, materials, equipment, tools and designs and can also bring unique skills and talents for specialised work. Many studies therefore address SC selection and focus on the criteria (and their relative weights) that contractors implicitly or explicitly use to select their SCs (Abbasianjahromi *et al.*, 2013; Hartmann and Caerteling, 2010; Hartmann *et al.*, 2009; Kumaraswamy and Matthews, 2000; Ramalingam, 2020; Ulubeyli and Kazaz, 2016; Ulubeyli *et al.*, 2010). Other studies focus on the resources of SCs, or the relationship between MC and SC (Aagaard *et al.*, 2015; Elazouni and Metwally, 2000; Gil *et al.*, 2001; Shafaat *et al.*, 2014; Tan *et al.*, 2017; Yik *et al.*, 2006).

Despite the attention for sub-contracting, literature barely addresses which level of design responsibility MCs sub-contract to SCs and how that affects projects. Particularly in the civil engineering industry, MCs struggle with this, which results in interface mismatches, design errors and a variety of other problems (Makkinga *et al.*, 2018; Zaneldin, 2016). The costs of such errors and rework can be substantial (Olanrewaju and Lee, 2022).

Considering that design responsibilities are increasingly pushed down to SCs nowadays, it is relevant to study which level of design responsibility MCs sub-contract to SCs and why. Few studies address this, but decisions made during the design stage can have a significant impact on following stages (Alsulamy, 2022; Zaneldin, 2016). This research bridges this gap in knowledge. In addition, this study addresses the impact of sub-contracting design responsibilities on project outcomes. Research on this is scarce too (Tan *et al.*, 2017).

Theoretical background

To better understand how and why MCs sub-contract design responsibilities to SCs, a literature review has been conducted. Three factors were found that MCs consider when deciding on the level of design responsibility to sub-contract. These are discussed next.

Sub-system complexity

In most projects, MCs separate the project into distinctive sections and sub-contract these sections or sub-systems to SCs (Abbasianjahromi *et al.*, 2016). One of the factors that MCs consider when deciding on a certain level of design responsibility to sub-contract, is the complexity of a sub-system. In literature, complexity is also referred to as "uncertainty," "specialisation," or "standardisation" of the work as factors that influence sub-contracting decisions (Gil *et al.*, 2001; Shafaat *et al.*, 2014). Literature states that when the sub-contracted work has vital unclear aspects and when the uncertainty is high, a switch from routine-mode to group problem-solving mode is made and teams consisting of MC and SC need to be formed to handle this uncertainty (Shafaat *et al.*, 2014). This means that SCs should get early access to decision-making and should be granted more design responsibilities when tasks are complex or uncertain (Franz *et al.*, 2013).

Literature also mentions less complex work and its relation to sub-contracting decisions. For example, the more standardised the sub-contracted work is, the more profitable a competitive relationship will be (Lee *et al.*, 2009). A competitive relationship means that the contractor selects the SC based on competition between several SCs and based on price comparison. However, to make it possible for SCs to determine a price, the MC needs to develop a rather detailed design in advance of the bidding process. This implies that the SC is involved rather late in the process and does not get much influence on the design. In addition, when the sub-contracted work is highly standardised, there is no real need to involve the SC in an early stage and to give the SC much influence on the design.

Interface complexity

Another factor that MCs consider when choosing a certain level of design responsibility to sub-contract are the number and complexity of interfaces between the part sub-contracted (sub-system), and the rest of the system (Makkinga *et al.*, 2018). An interface can be defined as (INCOSE, 2015, p. 263): “a shared boundary between two functional units, defined by functional characteristics, common physical interconnection characteristics, signal characteristics, or other characteristics, as appropriate (ISO 2382–1).” Interfaces are important because MCs separate the project into distinctive sub-systems and sub-contract these sub-systems to SCs. This leads to a fragmented structure of the project (Tserng and Lin, 2002). However, during design and development of the system, it must be ensured that, later, these fragmented sub-systems are adequately integrated into a complete functional system. This requires that the interfaces between the sub-systems must be managed carefully. Therefore, it is suggested that the more complex interfaces are, the more responsibilities the SC should get, because that makes it possible to coordinate and manage interfaces more effectively.

Level of experience

The third factor that MCs consider when choosing an appropriate level of design responsibility to sub-contract is the level of experience of the SC. Literature states that SCs may have a wealth of knowledge about the design process and the product itself (Franz *et al.*, 2013; Gil *et al.*, 2001; Lee *et al.*, 2009; Makkinga *et al.*, 2018; Shafaat *et al.*, 2014). This could be knowledge that the MC does not possess.

The knowledge and experience that the SC brings to the project can lead to faster and better design decisions. The mechanism behind this is that the experience of the SC simplifies complex decisions to routine (Shafaat *et al.*, 2014). This ensures that the SC can make appropriate decisions in the design stage without spending much time on that decision. Moreover, early involvement of the SC can improve the communication and coordination between designers and installers. When combining early involvement with design responsibilities, experienced SCs can positively affect project performance, or resolve conflicts without adding costs to the design process (Franz *et al.*, 2013; Gil *et al.*, 2001). However, MCs should carefully balance the complexity of the work to be sub-contracted to the knowledge, skills and experience of the SC (Makkinga *et al.*, 2018; Shafaat *et al.*, 2014). Therefore, it is suggested that SCs with more experience should get more design responsibilities and should be involved earlier in the design process than SCs with less experience.

Levels of design responsibility to sub-contract

In civil engineering projects, it is common to develop designs in phases and from abstract levels to detailed levels of design (Dinh and Dinh, 2021; Khan *et al.*, 2021; Zaneldin, 2016). Although the phases and levels of design detail are not strictly demarcated and vary across countries and projects, the basic principle of working stepwise from coarse to fine remains similar. The phases and levels of design detail can be associated to the different levels of design responsibility that MCs can sub-contract to SCs. At least three design levels can be distinguished: the preliminary design, the detailed design and production designs.

The preliminary design is an overall representation of the entire system so that the different elements and disciplines can be adjusted to one another. MCs can involve SCs already from this preliminary design stage and make SCs responsible for an entire sub-contracted part of the system, from preliminary design up to and including construction execution, and from abstract levels of detail to specific levels of detail.

The preliminary design is followed by the detailed design (sometimes an intermediate design is also present). This detailed design is a further iteration of the preliminary design. More details are worked out and the dimensions of the system are made definitive. For the detailed design, the different components of the system are worked out in such detail that these components can be bought from SCs and suppliers. When MCs involve SCs in the detailed design phase, the preliminary design is made by the MC and thus not included in the work of the SC. This means that the SC is involved at a later moment and must work out the details within the design boundaries set by the MC in the preliminary design.

The third level of design detail is the production drawings. These have the highest level of detail and are meant to prepare everything for the construction process on site. The production drawings are made at the beginning of the construction stage during work preparation (also called pre-construction) and are based on the detailed design. When MCs involve SCs no earlier than during work preparation, it means that the SC gets no design responsibilities in the preliminary design and detailed design phase. In this situation, the SC is involved rather late (no earlier than in the construction stage) and the design responsibilities involve making production drawings.

Key findings and research gap

The literature study revealed that a sound theory on sub-contracting design responsibilities has not yet been developed, because literature is fragmented and addresses a variety of topics in different industries. Particularly literature on sub-contracting design responsibilities in the civil engineering industry is scarce and has shown little progress towards theory development. Nevertheless, it is possible to derive the following propositions from literature.

Proposition 1. The complexity of the sub-contracted work, the interface complexity and the level of design experience of the SC are relevant factors that influence MCs' decisions on sub-contracting design responsibilities to SCs.

Proposition 2. The higher the level of complexity of the sub-contracted work and its interfaces and the more design experience the SC has, the more design responsibilities MCs give to SCs, and vice versa.

Proposition 3. When MCs give SCs the right level of design responsibilities (based on the complexity of the sub-contracted work, the interface complexity, and the level of design experience of the SC), few problems are to be expected in the design and construction stage of a project.

Based on these findings and focussing specifically on sub-contracting design responsibilities, the research question has been refined to: what is the impact of MCs' sub-contracting decisions (influenced by the complexity of the sub-contracted work, the interface complexity, and the level of design experience of the SC) on the design and construction stage of projects?

Methodology

A qualitative multiple case study was conducted to examine which level of design responsibility MCs sub-contract to SCs, the reasons for that level of responsibility and the impact of these decisions on the project. A qualitative research approach is appropriate as it allows examining concepts in terms of their meaning and interpretation in specific contexts of inquiry (Ketokivi and Choi, 2014). The case study is selected as it allows studying sub-contracting in-depth and within a real-life context (Eisenhardt, 1989; Yin, 2009).

From the three modes of conducting case research (Ketokivi and Choi, 2014) – theory generation, theory testing, theory elaboration – the theory elaboration mode was selected, because a sound theory on sub-contracting has not yet been developed (see theoretical background section). This makes deducing hypotheses, as required for theory testing, only partly possible. Theory elaboration is also preferred over theory generation, because in this research, it is preferred to make use of existing theory and that cannot be reconciled with the open approach that theory generation requires.

Successful theory elaboration requires the researcher to investigate theory and the empirical context simultaneously, in a balanced manner (Ketokivi and Choi, 2014). For this, abductive reasoning is emphasised. In the context of this research, abductive reasoning means modifying existing sub-contracting theory in order to reconcile it with sub-contracting in the specific context of the civil engineering industry.

Cases

The projects were selected from the project database from a civil engineering contractor in the Netherlands. Convenience sampling (Etikan *et al.*, 2016), theoretical sampling (Eisenhardt, 1989) and purposive sampling were used (Etikan *et al.*, 2016) to select cases. First, as access was given to the project database of one contractor, it was decided to use that database as it provided an opportunity to study information-rich cases (convenience sampling). From the database, projects were selected that were as much the same as possible (replication logic). This resulted in a list of bridge projects. Next step was to select only those bridge projects that included multiple and different sub-contractings (variation purposive sampling). This list was further reduced by selecting only those projects that each included the same type of sub-contracted sub-systems to make comparison possible (replication logic). This finally resulted in two bridge projects that each included three sub-contracting cases of the same type.

Two projects were found. Both were bridge projects, had the same public client, used a DandC delivery method, and involved similar sub-systems to be sub-contracted to SCs. Project A was the construction of a long bridge with multiple spans and support points. Project B involved the construction of several viaducts. The sub-contracting cases examined were the design and instalment of pre-fabricated beams, reinforcement and parapet barriers with railing (further on in the text: railing).

Data collection

Data collection techniques used were document reviews and interviews. In the document review, the contracts were analysed, as well as the requirements, memos, quality control documents, work plans, minutes and drawings. Most of these documents were found in the MC's digital project management environment.

In addition, employees of both the MC and the SC were interviewed to find out how and why sub-contracting decisions were made and how satisfied they were about the project. Interviewed were project leaders, design managers, engineers, purchasers, work planners and site managers. In total 18 semi-structured interviews were conducted. The results of the document study and the interviews were compared to increase the reliability and the validity of the findings (triangulation).

Data analysis

A within-case and cross-case analysis was conducted. The purpose of the within-case was to become intimately familiar with the case. Based on interview reports and documents, cases study write-ups were written by one of the researchers (Eisenhardt, 1989). The case descriptions were reflected upon by two other researchers. Emerging patterns were discussed and led to additional data collection. This process repeated until no more insights were gathered (data saturation).

In the cross-case, data was summarised in tables and analysed by applying data ordering techniques (Miles and Huberman, 1994). Cases were ordered in different ways to look for emerging patterns. For example, cases were ordered based on the factors that influenced sub-contracting decision-making, but also ordered on the sub-contracted responsibility and problems observed. From this cross-case ordering, patterns emerged, which were compared with the within-case data and existing theory. Differences were explained and reflected upon using abductive reasoning. This contributed to refining and extending theory (in the form of new propositions) and helped develop recommendations for practice.

Results

The next sections describe the within-case analysis and the cross-case analysis (Eisenhardt, 1989; Gorod *et al.*, 2021).

Within-case analysis

Sub-contracting A1 pre-cast beams. Regarding the beams in Project A, the MC considered sub-system complexity as high because the pre-cast beams needed to be tailored to the specific situation and required much technical knowhow for design, construction and instalment of the sub-system (e.g. complex beam shape). In addition, the beams had many physical interfaces with, among others, the joints, the sub-structure, the railing, the reinforcement and the road alignment and therefore the interface complexity was considered high too. The experience of the SC was also considered high because the SC had his own qualified in-house designers and a proven track record.

The MC decided that the SC should be involved from the very start of the design stage (from preliminary design and onwards) and should be given substantial design responsibilities, considering the complexities of the project and the experience of the SC.

A high level of detail was reached already in the preliminary design because of the experience of the SC. Apart from some disagreement about deflection and tolerances, the sub-contracting went very well in both the design stage and the construction stage, according to the parties involved. Both MC and SC were very satisfied.

Sub-contracting A2 reinforcement. With regard to the reinforcement in project A, the MC judged the sub-system complexity as moderately complex because the reinforcement had several degrees of freedom, but only few parameters were required for calculation. The reinforcement had some interfaces with, among others, the foundation and the pre-cast beams, but the importance of those interfaces was considered limited. The interface complexity was therefore judged moderately complex. Regarding the level of experience, the MC knew that the SC did not have much experience in designing reinforcement on such a large scale (low experience), but no other SCs were available.

The MC chose to sub-contract the reinforcement work from detailed design, up to and including work preparation and execution to make use of the experience of the SC.

The designers of the SC had much knowledge of buildability, leading to a design that was relatively easy to build. As a result, barely any problems occurred during construction. Although construction was successful, the SC experienced difficulties in designing reinforcement for this project. Verification showed that the models and drawings didn't meet all the standards and regulations. Sometimes more than five revisions were needed before the models and drawings met all requirements. Nevertheless, as this was considered a pilot project, both MC and SC anticipated problems and were still satisfied with this sub-contracting.

Sub-contracting A3 railing. Regarding the railing, the MC decided to reuse an existing design from a previous project. The railing was considered rather standard (low complexity). It didn't have many interfaces, but included some non-standard interfaces, and therefore the interface complexity was categorised as moderately complex. The SC had its own designers and experience in making detailed railing designs, but limited experience regarding integrating the railing design with the bridge design. The MC therefore categorised the level of experience of the SC as moderate.

The SC was selected to do the work preparation (production designs) and construction and had not been involved during the design stage. However, when the MC had finished the detailed design and handed it over to the SC, the SC found that some parts of the detailed design lacked dimensions and specific details. The SC solved these issues during work preparation, but it required changing previous designs. Despite some problems in the design stage, there were no noticeable problems during construction.

The MC and SC were moderately satisfied, but agreed that from a design point of view, it would have been better when the SC had been involved earlier. That could have solved the problem of design changes later in the process. However, the MC's purchasing department wondered if the benefits of involving the SC earlier in the design stage could have outweighed the purchasing advantages of late involvement and competitive bidding.

Sub-contracting B1 pre-cast beams. Regarding the pre-cast beams in project B, the MC considered the sub-system as complex, because the beams needed to be specifically tailored to the bridge. Also the interface complexity scored high, because the beams interacted with many other parts of the bridge and customised solutions for the interfaces were needed (high interface complexity). The MC knew that the SC was experienced in designing and installing such pre-cast beams and that they had in-house designers able to collaborate with the designers of the MC (high experience).

Because of all the complexities of the project, the SC was involved from the start of the design stage and made responsible for the preliminary design, production and instalment of the pre-cast beams for the bridge decks.

The SC was able to implement several optimisations. Furthermore, the MC and SC worked together well, for example by making agreements on the allowed tolerances on the deflection of the beams and by finding solutions to facilitate the water drainage of the viaduct through the beams. Barely any problems occurred in the design and construction stage, and both MC and SC were very satisfied.

Sub-contracting B2 reinforcement. Regarding the reinforcement in project B, one of the parties normally contracted by the MC was not available for this project. This forced the MC to work with another SC. The MC was not convinced of the level of experience of the SC, because the SC had not done work on this scale before. Therefore it was decided to sub-contract the SC no earlier than from work preparation (production designs) so that the MC could control the design process itself. The MC judged the reinforcement as moderately complex, because the reinforcement in this project was considered a standardised product that just needed some adjustments. The MC judged the interface complexity as moderately complex too, because the interfaces were more or less standard, though required some careful decision-making with regard to determining the most effective interfaces.

In this sub-contracting, there were several problems. It appeared that neither the MC, nor the SC had the employee capacity to make the detailed models and drawings, particularly considering the time pressure in the project. Therefore, it was decided to let the MC make the models, mostly with hired staff, and to sub-contract the making of the drawings to a third party. Due to all the delays earlier in the process, there was no time for improving the buildability of the designs. Consequently, the construction stage faced many problems. Design errors, among others caused by building information modelling (BIM) interoperability issues, resulted in reinforcement that was produced and delivered on the building site, but not installed due to late discovered design errors. The poor quality of the models, BIM interoperability problems and errors in drawings also led to an inefficient process for the reinforcement fixers. Both MC and SC were not satisfied.

Sub-contracting B3 railing. The MC made the SC responsible for a customised railing design that had to meet ambitious architectural demands, including maintenance for 25 years. In addition, the railing had to be certified and tested to make sure it could withstand the impact of a car. Based on these requirements and specifications, the MC considered the sub-system and interfaces as complex.

In previous projects, the SC had been involved no earlier than in the detailed design, but in this project, it was decided to deviate from routine because the railing had to be integrated with other elements, which was a rather challenging task. The experience of the SC was deemed necessary to deal with those challenges. Therefore, the SC was made responsible from preliminary design up to and including construction. The MC considered the SC as experienced with respect to designing and installing railings, but less with regard to integrating railing design with this challenging bridge design and thus judged the SC's design experience as moderate.

The SC was able to manage all these challenges and created a design that satisfied all parties involved. The calculation and verification documents, however, did not meet the required standards. Eventually, the SC solved this by hiring an engineering firm to make the calculations. During construction no problems with the railing were reported. The MC acknowledged that the experience of the SC had been truly necessary to deal with this kind of complex railing. Benefits mentioned were an optimised design, improved coordination regarding interfaces and less re-work. Both MC and SC were satisfied.

Cross-case analysis

Table 1 captures all the information of the cases, allowing for a cross-case analysis (Eisenhardt, 1989; Gorod *et al.*, 2021; Miles and Huberman, 1994).

The results in Table 1 confirm proposition 1 (see theoretical background section) that the complexity of the sub-contracted work, the interface complexity and the level of design experience of the SC are relevant factors that influence MCs' decisions on sub-contracting design responsibilities. The findings also support theory as to how these factors influence MCs' sub-contracting decision-making. The cases indeed show that the higher the level of complexity of the sub-contracted work and its interfaces and the more design experience the SC has, the more design responsibilities MCs give to SCs (e.g. cases A1 and B1). This was also supported vice versa (cases A3 and B2), which confirms proposition 2.

As all cases are in keeping with existing sub-contracting theory (proposition 1 and 2), few problems were expected in the design and construction stage (proposition 3). However, as can be observed in Table 1, this was only partly confirmed. Table 1 reveals that problems were reported in the two cases (A3 and B2) where the MC decided to involve the SCs no earlier than in the construction stage for making production designs. These findings motivated an elaboration of existing sub-contracting theory, explained in the next section.

Discussion

This section presents a discussion to further elaborate theory by combining existing theory with empirical data to establish and refine key concepts and causal relationships.

Impact of sub-contracting decisions. Table 1 reveals that proposition 3 was confirmed in four of the six cases but contradicted the two cases (A3 and B2) where the MC decided to involve the SCs no earlier than in the construction stage for making production designs. Although this decision is in keeping with literature considering case characteristics (low or moderate sub-system and interface complexity, and low or moderate SC experience), there

Table 1.
Cross-case comparison

Case	Sub-system complexity	Interface complexity	SC experience	Sub-contracted responsibility	Project impact	MC and SC satisfaction
A1	high	high	high	Preliminary design	No noticeable problems were reported in the design and construction stage. Benefits mentioned were a higher level of detail reached in the preliminary design because of the experience of the SC	Very satisfied (both)
B1	high	high	high	Preliminary design	No noticeable problems were reported in the design and construction stage. Benefits mentioned were that the SC brought forward several optimisations, e.g. solutions to facilitate the water drainage of the viaduct through the beams	Very satisfied (both)
B3	high	high	moderate	Preliminary design	Verification and calculation issues were reported in the design stage, but no problems in the construction stage. The MC acknowledged that the experience of the SC had been truly necessary to deal with this kind of complex railing. Benefits mentioned were an optimised design, improved coordination regarding interfaces and less re-work	Satisfied (both)
A2	moderate	moderate	low	Detailed design	This project was considered a pilot. In the design stage, models did not meet standards and regulations and several revisions were needed to correct this. Benefits reported were that the rebar specs could be generated directly from the 3D reinforcement models, which led to a cheaper and more efficient design. Construction was successful	Satisfied (both)
A3	low	moderate	moderate	Production design	The SC detected errors in the MC's reused design but corrected this, resulting in design changes of the detailed design. MC and SC agreed that from a design point of view, it would have been better when the SC had been involved earlier. That could have reduced the number of design changes. However, the MC's purchasing department wondered if earlier involvement of the SC could have outweighed the purchasing benefits. Construction was successful	Moderately satisfied (both)
B2	moderate	moderate	low	Production design	Issues reported in the design stage were a lack of design capacity, poor models, inadequate drawings and BIM interoperability issues. During construction, materials were delivered on site, but could not be used because of (too) late discovered design errors	Not satisfied (both)

were still several problems in the design and/or construction stage (see Table 1). Moreover, the MCs and SCs involved in these cases were least satisfied compared to all cases studied. Because the empirical findings of this study partly oppose literature, the following proposition was developed to question and refine existing theory and stimulate further theory elaboration on this point.

Proposition 4. Sub-contracting theory assumes that few problems are to be expected in the design and construction stage of projects when MCs carefully fit the level of SCs' design responsibility to project characteristics (in terms of the complexity of the sub-contracted work, the interface complexity and the level of design experience of the SC). This theory is best suited when project characteristics suggest sub-contracting design responsibilities to SCs in the design stage.

This new proposition suggests that it is recommended to give the SC responsibility already in the design stage to prevent problems in later stages. This is in keeping with other studies, which state that the design stage can have a significant impact on later stages in construction projects (Alsulamy, 2022; Khan *et al.*, 2021; Zaneldin, 2016). However, it contrasts with other literature that states that late involvement (construction stage) of the SC is considered a preferred way of sub-contracting, despite negative characteristics (Lee *et al.*, 2009). Late involvement of the SC is seen as a means to achieve a purchasing advantage (e.g. bid shopping). Therefore, an additional proposition can be formulated, challenging existing theory and calling for additional research.

Proposition 5. Involving the SC no earlier than in the construction stage can lead to purchasing advantages (existing theory), but also to problems in the design and production stage (this study).

Transferring sub-contracting documents from MC to SC. The two cases where the most problems were observed (case A3 and B2), were those where the MCs decided to involve the SCs no earlier than in the construction stage for making production designs. In both cases, it was found that problems were caused by a late involvement of the SC in combination with problems related to transferring sub-contracting documents from MC to SC. In case A3, problems were caused by the MC transferring a re-used and partly inaccurate design to the SC, and because the SC was involved no earlier than in the construction stage, design errors were discovered late. This led to a series of design changes, which required additional time and effort to implement.

In case B2, there were also problems related to transferring sub-contracting documents from MC to SC, but in this case the MC wanted to transfer sub-contracting documents to the SC via BIM systems. However, it appeared that the MC's and SCs BIM systems were not compatible. This triggered a cascade of problems that started with compatibility/interoperability problems, but ultimately led to reinforcement delivered on site that could not be used.

These findings imply that apart from the factors sub-system complexity, interface complexity and SC experience, MCs should also carefully check the quality of the sub-contracting documents and consider how to transfer these to the SC. Particularly when the MC prefers to involve the SC no earlier than in the construction stage. Based on this, a new proposition was developed, adding decision-making factors to existing sub-contracting theory.

Proposition 6. IF MCs involve SCs no earlier than in the construction stage, AND when sub-contracting documents provided by the MC to the SC are of low quality OR provided in a form that the SC cannot handle, THEN there is a risk of problems occurring in the design and construction stage.

Project management. Case B2 revealed that apart from late involvement of the SC (proposition 5), and problems related to transferring sub-contracting documents from MC to SC (proposition 6), even more factors played a role in explaining the problems and undesired outcomes. These factors are related to project management. Case B2 revealed that the BIM interoperability problems could not be solved effectively because of time pressure and a lack of employee capacity at both MC and SC. Due to all the delays earlier in the process and lack of employees, there was no time to carefully check designs and implement suggestions for improving the buildability of the designs. This resulted in several problems. Based on these findings, the final proposition was developed, extending proposition 6.

Proposition 7. IF MCs involve SCs no earlier than in the construction stage, AND when sub-contracting documents provided by the MC to the SC are of low quality OR provided in a form that the SC cannot handle, AND when there is no time and employee capacity available to correct these problems, THEN there is a **high risk** of problems occurring in the design and construction stage.

Contribution to practice

This study contributes to practice as it revealed that next to the complexity of the sub-contracted work, the interface complexity and the level of design experience of the SC, practitioners also need to consider the quality of sub-contracting documents, BIM interoperability, time pressure and employee availability.

This study also recommends that practitioners adopt a more deliberate stance on sub-contracting low levels of responsibility to SCs. Project leaders, designers and purchasers should carefully balance potential purchasing advantages and disadvantages, with the benefits that can be achieved when SCs are given more design responsibilities.

These recommendations can help practitioners make more informed and evidence-based sub-contracting decisions.

Limitations and future research

This study revealed four new sub-contracting factors that have an impact on the design and construction stage of projects. These factors are the quality of sub-contracting documents, BIM interoperability, time pressure and employee availability. However, the relative importance of these factors could not be determined based on the empirical data available. Future research could try to establish the roles and impact of each factor. For example, by comparing the outcomes of sub-contracting cases where these factors are present to a greater or lesser degree.

In addition, existing theory states that involving the SC no earlier than in the construction stage can lead to purchasing advantages (bid-shopping), but this study reveals that it can also lead to problems in the design and construction stage. However, as successful bid-shopping cases were not available in this study, future studies could try to determine more precisely under which circumstances late involvement of the SC and bid-shopping is beneficial. This could be done by studying successful bid-shopping cases and comparing the results with the outcomes of this study.

Finally, future research could include data from multiple MCs and include different types of sub-contractings in a variety of projects. In this study only six sub-contracting situations have been studied, in two projects from one MC.

Conclusion

In this study, it is explored which level of design responsibility MCs sub-contract to SCs, for what reasons and what the impact of these decisions is on the design and construction stage of projects. Six sub-contracting cases were examined in two civil engineering projects, revealing that existing sub-contracting theory is best suited when project characteristics suggest sub-contracting to SCs in the *design* stage. However, when MCs involve the SC no earlier than in the construction stage, existing theory needs refinement. In this study, this refinement is presented in the form of propositions. These state that next to the complexity of the sub-contracted work, the interface complexity and the level of design experience of the SC, also the quality of sub-contracting documents, BIM interoperability, time pressure and employee availability should be considered. This research adds value to the broader field of sub-contracting as it revealed these new factors and provides new insights in causal relationships between the level of sub-contracting design responsibilities and its impact on the design and construction stage of projects.

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