Knowledge-based Design Cost Estimation Through Extending Industry Foundation Classes

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Abstract: In order to overcome divergence of estimation with the same data, the proposed costing process adopts an integrated design of information system to design the process knowledge and costing system together. By employing and extending a widely used international standard, industry foundation classes, the system can provide an integrated process which can harvest information and knowledge of current quantity surveying practice of costing method and data. Knowledge of quantification is encoded from literatures, motivation case and standards. It can reduce the time consumption of current manual practice. The further development will represent the pricing process in a different type of knowledge representation. The hybrid types of knowledge representation can produce a reliable estimation for construction project. In a practical term, the knowledge management of quantity surveying can improve the system of construction estimation. The theoretical significance of this study lies in the fact that its content and conclusion make it possible to develop an automatic estimation system based on hybrid knowledge representation approach.

1 INTRODUCTION

Researchers and professionals have continued to address the importance of cost estimation to construction industry. Accurate cost estimation is a core foundation to construction project successfulness. Moreover the most widely used design costing model is quantity-based cost estimation model (Akintoye and Fitzgerald, 2000). The quantity-based relationships between product and cost information are helpful in assisting quantity surveyors with the creation of estimates.

Quantity surveying is a knowledge-based, dynamic and collaborative process and evolves with variance and up-to-date evidence. With the development of information technology, many activities of quantity surveying such as cost itemization, quantification, and pricing are being supported by computer aided design system, quantity taking off system, and spread sheet which have already being integrated into core business of quantity surveying company. If the knowledge accumulated in these systems can be shared, communicated and integrated together during the execution of cost estimation, the costing practice can be well monitored.

However, the quantity surveying knowledge has not been integrated into the process of cost estimation; the knowledge in the current system has not been represented neither. Even though there are various applications to support quantity surveying practice, for example CostX, and Nomitech (Exactal, 2013; Nomitech, 2013). They can only support certain part of cost estimation instead of the whole process. Consequently in order to keep the accuracy of cost estimation, many of these efforts require substantial manual input including remodelling the product model into process model which is time consuming, error prone and tedious task, and the user acceptance of such application is low (Forgues and Iordanova, 2012; Tanyer and Aouad, 2005). Recently with the emergence of industry foundation classes (IFC) in architectural, engineering, and construction (AEC) industries opportunities exist for improving costing processes. However, both of our case study and one quantitative study of BIM's impact on detailed cost estimation reveals that the impact on costing practice of IFC is still remaining

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on the junior level of quantity surveyor which his major task is calculating product based quantities of a construction project (Shen and Issa, 2010; Xu and Tang, 2011).

In order to meet this challenge this paper proposes a knowledge extension on IFC. We attempt to extend IFC with the built-in knowledge by analysing sources of quantity surveying knowledge for where we consider (1) construction classification system (2) standard documents (3) published literatures (4) tacit knowledge of domain experts (5) cost data in current database application. It is expected to make use of quantity surveying knowledge to support and optimize costing process by delivering accurate quantity and reliable price of cost items. Firstly, we examine current detailed cost estimation process and specify the knowledge spaces along the process. After that we elaborate the knowledge within the IFC environment to provide the capability for decision support to costing process. It provides the foundation of the development of detailed cost estimation system. By combining the built-in intelligence of IFC with above mentioned research efforts we can further improve the automation of cost estimation. Finally we illustrate the application of knowledge-based IFC to derive cost estimation on a construction product as a motivation case.

2 PROCESS OF CONSTRUCTION COST ESTIMATION

The detailed cost estimation models the distributions of each cost element in a building via bill of quantities. In order to demonstrate the process of cost estimation at LOD 300, direct observation has been conducted. Study shows that in a detailed construction cost estimation process, cost itemization is the first step of cost estimation. It is the process of decomposing and re-categorizing building components based on cost break-down structure and standard method of measurement (Dell'Isola, 2003; Hietanen, 2000; Royal Institution of Chartered Surveyors, 2011). Measurement standards have been published to help quantity surveyor to decomposing building components, however an empirical study indicates that quantity surveyor will select the most possible working method based on their experience (Tan and Makwasha, 2010).

The most common complaint from professional quantity survey or about quantity surveying in costing practice was that they are so busy dealing with assumptions that has no time to monitor their process. In order to reveal assumptions made in the detailed cost estimation from professional quantity surveyor, we further investigated the documents provided by professional quantity surveyor. Focusing on LOD 300 phase, by given specific assembles, cost estimation is predicting the construction works at LOD 400 phase and LOD 500 (Xu and Tang, 2011). As a result there are large numbers of assumptions that need to be made during this stage and it is time consuming and error prone process, refer to table 1 the difficulties of doing cost estimation.

Table 1: The difficulties of applying resource based costing model.

Problems	Difficulties
Inadequate Interoperability	• Lack of understanding of construction process (Bowen and Edwards, 1985; Skitmore and Patchell, 1990); • No available data (Ashworth, 2004; Fortune and Lees, 1996); • Traditional fragmentation of the design and construction functions (Love et al., 1998).
Unregulated Assumptions	• Additional assumptions (Skitmore and Marston, 1999); • Lack of understanding of resource based cost model (Fortune and Lees, 1996); • Different data requirements (Kim et al., 2004).
Others	• Time constraints (Akintoye and Fitzgerald, 2000).

In our study, we divide the transcript process into three steps, which are cost itemization, quantification and pricing. These three steps should be discussed separately because of the different type of knowledge. Institutions like Royal Institution of Chartered Surveyors and American Institute of Architects defines how quantity surveyor should estimate the quantities of buildings (Royal Institution of Chartered Surveyors, 2011).

In order to fully understand the quantity surveying practice in detailed cost estimation based on existing system, an analysis of cost items is required. In the case study there are 108 cost items for each building, and the whole project have 14 buildings. We listed three common cost items to demonstrate the classifiers we have acquired, see table 2. For example MU10 standard brick is product, masonry with M10 cement mortar is working method.

Therefore, there are four classifiers need to be

Table 2: Examples of cost items in case study.

NUM	Section	Cost items	Classifiers
1	Masonry	External Wall, MU10 standard brick, masonry with M10 cement mortar	[Building component]+[Construction Product] +[Working method]
		240mm thickness，below elevation ±1.1	[Product’s property: thickness]，[Applied Location]
2	Finishes	‘911’ Waterproof non-tar polyurethane coating	[Construction Product]
		1.2mm thickness, applied at bathroom floor	[Product’s property: thickness]，[Applied Location]
3	Finishes	1:3 cement mortar, trowel compaction	[Construction Product] +[Working method]
		20mm thickness, applied at floor	[Product’s property: thickness]，[Applied Location]

identified, i.e. building component, construction product, product property, and location. In practise, cost estimator have two options that could complete the working method attach to construction product. Firstly cost estimator would like to form up certain working method based on their experience, design specification and discussion with design team. Secondly cost estimator would refer to cost data base to check available of existing working methods and select the most possible one based on their experience. Commercially available of cost database facilitate the second approach of forming up cost items, e.g. R.S. Means, and Building Cost Information Service (BCIS).

3 KNOWLEDGE IN DESIGN COSTING

The process-related knowledge which means the type of knowledge is used by quantity surveyors when an estimation process is being executed (Seethamraju and Marjanovic, 2009). Furthermore we classified knowledge into two further subtypes: concepts and rules that support process-related activities efficiently through the creation of cost estimation. The concepts describe all the building components and concepts related to construction cost estimation in order to form the basis of cost estimation, there are more than 6000 concepts (El-Diraby et al., 2005). Therefore we are not including all the concepts but mainly provide the categories along the costing process, please see table 3.

The rules further specified the details of the activities such as when and how certain calculation must be executed.

After cost itemization, we have differentiated construction product with cost item, for each cost item, standard method of measurement specified the corresponding rules respectively, including the unit and the deduction rules. Table 4 shows the rules in the standards in order to get the actual quantity of a construction product. Particularly the knowledge of quantity calculation designs a control structure that triggers the calculation operation when the conditions become true.

Table 3: Description of Concept-based Knowledge.

Targeted Process	Concepts Category	Description
The whole construction process	Building components classification system	The classification system involves all construction concepts, including different application domains. For example OmniClasses, MasterFormat, and ISO 14177.
Cost Itemization	Working breakdown structure	This document provides the template of breaking down a construction project in a hierarchy structure and is well documented by professional intuitions, e.g. RICS, AACE. It has three typical structures depend on the division of component and has 61 sections. For example New Rules of Measurements (Royal Institution of Chartered Surveyors, 2011).
Quantification	Construction products relationships	Construction products are derived from building components, thus their quantities are related but may not same. For example IFC modelled wall and it’s related finishes (buildingSMART International Limited, 2013)
Pricing	Cost item database	The database records common construction product and its labour cost and material cost. The data descript productivity and labour sources. A typical commercialized database is being developed by R.S. Mean Company.

Table 4: Description of Rule-based Knowledge.

Targeted Process	Category of rules	Description
Quantification	Deduction rules	Depicting different situation that applying different deduction rules. For example Damp-proof courses less than 300mm wide should be measured in length, and Damp-proof courses more than 300mm wide should be measured in square meter etc. In production rules, it can be translated as if the damp-proof is wider that 300mm, then measure it in square meter.

Regarding pricing stage, practitioners support subjective probability distributions, firstly due to the fact that in the construction industry relevant data seem to be lacking or is not organized in a way that allows it to be used for analysis. Secondly, as Flanagan & Norman (1983) highlighted, cost management in construction seems to be based on feel and experience therefore modelling should incorporate some form of expert judgement.

Expert judgement has to be exercised on the relevance of the inputs or data to be used for estimation of project costs. It seems though that in practise there is no consensus on the degree to which subjective is applied as some practitioners also decide on the correlation between cost items or elements based on personal experience and judgement rather than historical data.

4 KNOWLEDGE-BASED EXTENSION TO IFC

Industry Foundation Class (IFC), was developed by buildingSMART and is a common data 'schema' intended for holding interdisciplinary information for building lifecycle in a building information model, and exchanging it among software applications used in AEC (BuildingSMART UK, 2010). A schema, often called 'Product (Data) Model', is captured in IFC specification, and composed of (1) entities, (2) attributes, and (3) relationships between entities. Schema defines the way by which the population of these entities and relationships needs to be represented.

The ultimate goal is to determine the cost of construction project from design results by using IFC. As a first step, a formal description of the IFC data model and related building information data models (such as material databases) such that they can be used by a formal rule language need to be established (Staub et al., 2003). This kind of knowledge representation can be derived from quantity surveyor's rationale and the same research efforts are leading by (Staub and Nepal, 2007). Thus based on this ontology language and decomposing mechanism a further development can be carried out (Xu et al., 2013).

We employ hybrid knowledge management techniques, which are solver and rule (Holsapple and Whinston, 1996). In our study the solver is an executable algorithm that can solve one particular class of problem and rule is the underpinning reasoning knowledge. Particularly in this paper we are focusing on rules.

The process of IFC based cost estimation presents an automatic decomposing building element into construction products, semi-automatic classifying construction products into cost items, automatically taking off quantities for cost items, and pricing each cost items (Xu et al., 2013). The extension to IFC is the rule-based knowledge, and attempts to integrate the knowledge into IFC in order to automate the described cost estimation process.

In order to illustrate our knowledge extension to IFC, it is essential for us to present the process of cost estimation process in IFC, see figure 1. It is not the main focus of this paper, but briefly the application harvests information from BIM objects in various manners – either enhancing object definitions within the model, using a classification system to link objects to more detailed information stored externally from the BIM application in a database. The design of this particular costing application split the databases into design results database (specified in IFC), cost value database (realized in R.S. Means cost information company), and cost knowledge database (proposed cost knowledge base) rather than traditional cost database that records company's core competence in the form of cost items' value and leave the cost knowledge to individual quantity surveyors. On the other hand, IFC data modelling is based on EXPRESS data modelling language is that combines ideas from the entity-attribute-relationship family of modelling languages with object modelling ideas of the late 1980s. Wermelinger and Bejan (1993) describe a mapping of EXPRESS into conceptual graphs (CGs). Thus our first step is translating the domain rules

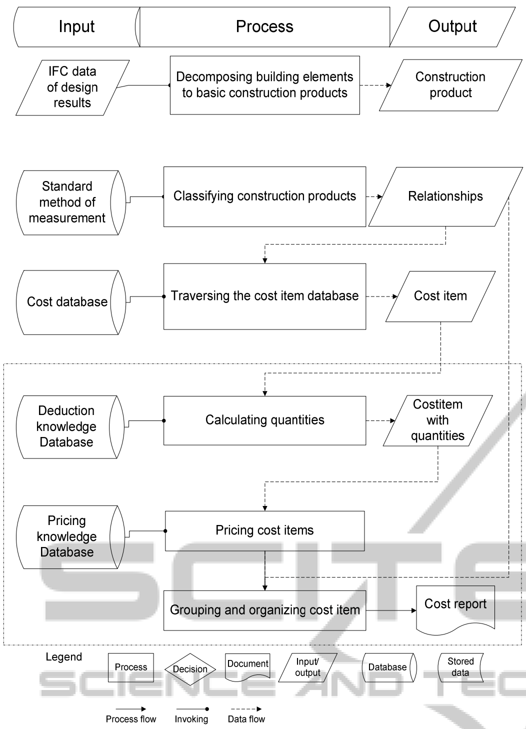


Figure 1: Cost estimation process in IFC.

into CGs which can be evaluated by domain experts.

This kind of rule can be expressed by corresponding entities in IFC. Building Element is expressed by IfcBuildingElement and with subtype of IfcWall, IfcColumn, IfcSlab etc; HasCovering relationship is defined by IfcRelCoversBldgElements; Finishes is defined by IfcCovering; ElementQuantity is expressed by IfcElementQuantity; HasVoids is expressed by IfcOpeningElement and subtype of IfcWindow and IfcDoor; HasVoids area is expressed by IfcElementQuantity assigned to IfcOpeningElement; Subtraction calculation is expressed by IfcFeatureElementSubtraction.

RICS defines that no deduction is made for voids not exceeding 1.00m2; Boundary work to voids is only measured where the void exceeds 1.00m2, and is measured by length (Royal Institution of Chartered Surveyors, 2011, p. 152). The translation of the domain rule is straightforward after identified static knowledge of construction. Take a piece of ‘knowledge’ as follows:

QS measures the quantities of finishes in area and created boundary works.

The IFC model defines a flexible and powerful mechanism that allows extensions to the model through the use of the IfcPropertySet entity. An IFC property set could be used to define a set of properties (IfcProperty entities or other nested IfcPropertySet entities), and can be linked to any number of IFC objects using the IfcRelAssignsProperties entity. Using this approach, we could, for example, define a property set that describes the specifications of a building element and link this set to the IfcProduct entity that represents a specific building element using an IfcRelAssignsProperties entity (Halfawy and Froese, 2002).

Thus we can apply deduction rules using similar approach. A new IfcEstimationDef entity could be created as a container for object-related rules and procedures, both of which are supported by

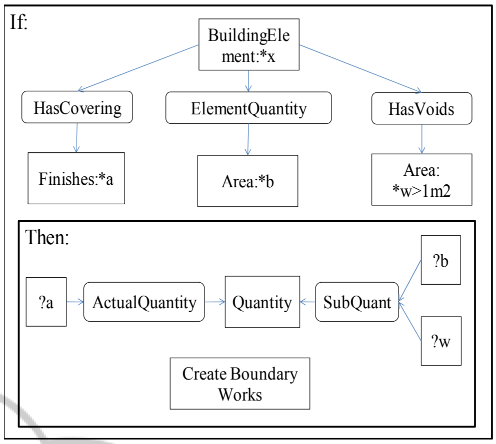
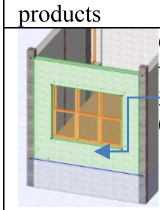


Figure 2: A Conceptual Graph of Quantity surveying rule.

Table 5: A decent representation.

measuring(e)	e is a measuring ‘event’
agent(e, QS)	QS was the measurer
unit(e, area)	measured unit was area
∃b, buildingelement(b) ∧ finishes(f, b)	Building element b has finishes f
∃f, finishes(f) ∧ object(e, f)	A covering f is the object of measuring
voids(e, w)	measured voids was w
∀e,f,w,area measuring(e)∧ unit(e, area) ∧object(e, f) ∧ voids(e, w>1) → quantity(e, b-w) ∧ creates(boundaryworks)	If a building element x has covering a, has an element quantity of area b, has a void area larger than 1m^2, then the actual quantity of covering a is the subtraction of b and w and create new cost item boundary work

Table 6: Components of Rule-based Knowledge.

Design model and corresponding construction products	Situation	Corresponding deduction rule	Quantity takeoff result
 Ceramic wall tile, 33cm*33cm*0.8cm	3.5m*5m wall area is covered by tile; The tile size is 0.33m*0.33m (Tile is traded by piece and need to be cut in order to cover the boundary of the applied locations) The wall area is 17.5 m^2 and with opening voids of 1.3*2.4=3.21 m^2	Wall area – Opening area Plus, create new cost item: Boundary work of window edge Net girth of window	A= 17.5-3.21=14.29m^2 B=(1.3+2.4)*2=7.4m

the EXPRESS language. The linkage between IfcEstimationDef entity and any number of IFC entity can be realized by using the defined relationship entity called IfcRelAssignsEstimation. Unstructured knowledge, in the form of documents, can be defined using properties in a property set linked to the object.

In a typical IfcEstimationDef entity, rules may refer to the attributes of same object or other object. To execute these rules, IFC application would need to implement or to interface with a rule-based engine, and the engine should be examined in a further research. Also, the procedures are defined by their interface and could be implemented using standard component interfaces. Objects would need to access these components to execute these procedures. For example, an "CalculateBoundaryWorksQuantity" procedure may be implemented in a standard interface, to compute and create the boundary works. Other procedures could be implemented to check some object values or to retrieve some data (e.g. form an online product repository).

5 APPLICATION OF KNOWLEDGE-BASED IFC

We are using life example to demonstrate the process of cost estimation. We take a building element 'wall' as an example. The products and its relationship with building element are created in IFC after this step. The relationship would be stored for further use and construction products need to be carried to next process. Furthermore, Ma et al. (2013) indicate that fully automatic of decomposing process can be accomplished in IFC.

The information available in this case indicates *the wall area has finishes of tile, which has property of 33cm*33cm*0.8cm, using adhesive set; the wall's area is 17.5m^2, has opening window of 1.3m*2.4m*

The actual quantity of finishes: tile should be 14.9 m^2 with 7.4 m boundary work. Refer to table 6 Components of Rule-based Knowledge. Based on the knowledge we specified in previous section, we can identify that there are two cost items. They are the tiles and boundary works, which the quantities are showing in the table.

There is, however as discussed previous, a danger of applying published data or software database pricing without first adjusting for the particular aspects of the project currently under consideration. In construction every project is unique, with a distinct set of local factors (such as size of project, desirability, level of competition, flexibility of specifications, work site conditions, hour restrictions etc.) that come into play in current project. Previously, when an estimating system is used that is attached to a price database, the professional estimator would still have reviewed each line of the item price to determine if it is applicable to the project being estimated, as pricing and estimation is captured within one entity.

In order to demonstrate the process of selection of working methods and pricing process, the cost database has been examined as well as the price analysis process. There are approximately 1000 items in each cost breakdown sections, we only illustrate the finishes and tile section and focusing on the flooring tile. We execute 54 cost items in ceramic tile in R.S. Means construction cost database. And manually decomposing the cost items based on our classification conditions and has been reorganized respectively, e.g. product types, product property, applied area, geometric shape, and working methods. Based on the example we provided, cost item: Ceramic flooring tile, 33cm*33cm*0.8cm, applied in external wall, thus we can list three possible cost item records which represents three different working methods.

The daily output or productivity recorded in commercial database is based on several factors: R.S. Means' engineer's experience, trade labour productivity publications, contractors' input, and in

Table 7: Reorganized Cost Database.

Construction product	Applied area	Product property	Working method		Crew	Daily Output	Labour Hours	Unit	Material	Labour	Total
Ceramic tile	External Wall	33cm x 33cm tiles	adhesive set	using 0.8cm high piece	D7	8.93	1.8	m2	$45.45	$64.8	$110.25
Ceramic tile	External Wall	33cm x 33cm tiles	adhesive set		D7	13.94	1.17	m2	$42.58	$42.12	$84.7
Ceramic tile	External Wall	33cm x 33cm tiles	adhesive set	with 140.25cm x 140.25cm tile wainscot	D7	5.7	2.81	m2	$77.78	$101.16	$178.94

some cases actual time and motion study observation. Labour hours calculated by dividing the crew labour hours worked in a day by the daily output. Note: Multiply labour hours by 60 to convert to hours and minutes. Crews have already been determined for each cost item, detailed crews information can refer to R.S. Means cost database reference: Crew standard Union

Based on traversing the cost database, we acquired three possible working methods in adhesive set, due to no further information revealed; professional quantity surveyor will assume the uniform distribution of such method. Thus it is common that professional will take the average of possible methods that can represent the most possible unit price and productivity. Thus this process will be the further investigation in our research.

6 DISCUSSION AND FUTURE WORKS

Ma et al., (2013) demonstrate the costing process for building structure in IFC, based on their decomposing process that we can further extend IFC into finishes of building by incorporating surveying knowledge and pricing knowledge. Meanwhile there is little research on quantity surveying knowledge (Senaratne and Sabesan, 2010). Hence without incorporate the knowledge into the process it is difficult for applications to deliver a completed costing report. Thus this gap highlights the contribution of our research.

In practical term, knowledge management of quantity surveying can improve the system of construction estimation. The theoretical significance of this study lies in the fact that its content and conclusion make it possible to develop an automatic estimation system. Furthermore the combination of knowledge representation and automatic system development can establish a sustainable development loop of construction cost estimation digitalization.

This paper provides the initial result from the motivation case of a knowledge based approach and more evidences are required to further evaluate this work, for instance a real case study with empirical results and prototype of the system. Meanwhile, the reasoning process, inference engine and system architecture will be further investigated in order to reveal the pricing stage of quantity surveying.

Furthermore certain conclusion can be made is that a hybrid knowledge representation of quantity surveying is essential to develop an estimation system. As delivering a reliable estimation of construction project, two steps are essential. Quantification step is incorporated with rule-based knowledge representation. And pricing step is incorporated with other knowledge representation type. Thus a hybrid knowledge representation can enable the development of an automatic estimation system via quantity surveying approach in future.

REFERENCES

Akintoye, A., Fitzgerald, E., 2000. A survey of current cost estimating practices in the UK. *Constr. Manag. Econ. 18*, 161–172.

Ashworth, A., 2004. *Cost studies of buildings.*

Bowen, P.A., Edwards, 1985. Cost modelling and price forecasting: practice and theory in perspective. *Constr. Manag. Econ. 3*, 199–215.

buildingSMART International Limited, *2013. IFC Standard* (WWW Document). URL about:blank (accessed 3.31.13).

BuildingSMART UK, 2010. *Investing in BIM competence BuildingSMART: a guide to collaborative working for project owners and building professionals, Endeavour.* UK.

Dell'Isola, M. D., 2003. Detailed Cost Estimating. *Excerpt from Archit. Handb.* Prof. Pract. 1–13.

El-Diraby, T., Lima, C., Feis, B., 2005. Domain taxonomy for construction concepts: *toward a formal ontology for construction knowledge*. *J. Comput. Civ.* … 394–406.

Exactal, 2013. CostX® | *Exactal CostX : Construction Estimating Software | On-screen Takeoff Software* (WWW Document). URL http://www.exactal.co.uk/ products/costX (accessed 11.4.13).

Flanagan, R., Norman, G., 1983. The accuracy and monitoring of quantity surveyors' price forecasting for building work. *Constr. Manag. Econ. 1*, 157–180.

Forgues, D., Iordanova, I., 2012. Rethinking the Cost Estimating Process through 5D BIM: *A Case Study. ... Res. Congr. 2012* … 778–786.

Fortune, C., Lees, M., 1996. The relative performance of new and traditional cost models in strategic advice for clients. *RICS Res.* Pap. Ser. 2.

Halfawy, M., Froese, T., 2002. Modeling and implementation of smart AEC objects: an IFC perspective. In: *CIB W78 2002 Conference,* Aarhus, Denmark. pp. 12–14.

Hietanen, J., 2000. *Quantity Takeoff using IFC R2 . 0.*

Holsapple, C., Whinston, A., 1996. Decision Support Systems: *A Knowledge-Based Approach. Course Technologies*, Cambridge, MA.

Kim, G.-H., An, S.-H., Kang, K.-I., 2004. Comparison of construction cost estimating models based on regression analysis, neural networks, and case-based reasoning. *Build. Environ. 39*, 1235–1242.

Love, P.E.D., Gunasekaran, A., Li, H., 1998. Concurrent engineering: a strategy for procuring construction projects. *Int. J. Proj. Manag. 16*, 375–383.

Ma, Z., Wei, Z., Zhang, X., 2013. Semi-automatic and specification-compliant cost estimation for tendering of building projects based on IFC data of design model. *Autom. Constr. 30*, 126–135.

Nomitech, 2013. Nomitech Construction Oil & Gas BIM Cost Estimating Software, *Estimating Services | Home* (WWW Document). URL http://www.nomitech.eu/ cms/en/c/index.html (accessed 11.4.13).

Royal Institution of Chartered Surveyors, 2011. *RICS New Rules of M EASUREMENT Bill of Quantities for Works Procurement.*

Seethamraju, R., Marjanovic, O., 2009. Role of process knowledge in business process improvement methodology: *a case study. Bus. Process Manag. J. 15,* 920–936.

Senaratne, S., Sabesan, S., 2010. Managing knowledge as quantity surveyors: An exploratory case study in Sri Lanka. Built-Environment Sri Lanka 8, 41–47.

Shen, Z., Issa, R., 2010. *Quantitative evaluation of the BIM-assisted construction detailed cost estimates. Pap. Constr. Manag.*

Skitmore, M., Marston, V.K., 1999. *Cost Modelling. E&FN Spon.*, London.

Skitmore, M., Patchell, B., 1990. *Developments in contract price forecasting and bidding techniques. Quant. Surv. Tech. New* … 75–120.

Staub, F.S., Fischer, M., Kunz, J., Ishii, K., Paulson, B., 2003. A feature ontology to support construction cost estimating. *Artif. Intell. Eng. Des. Anal. Manuf. 17*, 133–154.

Staub, F. S., Nepal, M. P., 2007. Reasoning about component similarity in building product models from the construction perspective. *Autom. Constr. 17,* 11–21.

Tan, F., Makwasha, T., 2010. " Best practice " *cost estimation in land transport infrastructure projects 1–15.*

Tanyer, A. M., Aouad, G., 2005. Moving beyond the fourth dimension with an IFC-based single project database. *Autom. Constr. 14,* 15–32.

Wermelinger, M., Bejan, A., 1993. *Conceptual Structures for Modeling in CIM.*

Xu, S., Liu, K., Tang, L. C. M., 2013. Cost Estimation in Building Information Model. *In: International Conference on Construction and Real Estate Management (ICCREM 2013).*

Xu, S., Tang, L.C.M., 2011. BIM Environment : Quantity Surveyor ' s Information Lifecycle. *In: The Innovation and the Built Environment Academy.*