

AN EXPLORATORY STUDY OF INFORMATION MATURITY IN CONSTRUCTION AND DEVELOPING A DECISION-MAKING MODEL

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The efficiency of a design process has a close relationship with effective information management. However, the increasing volume of digital information makes effective information management in design and construction organisations more difficult, in particular in retrieving high value, high quality and, more importantly, “mature” design information when it is needed. There is a need to develop a tool that can assess, or indeed increase, the maturity of any design information for ease of storage, retrieval and reuse with suitable information management tools. The engineering industry has been striving for this for many years, and has been successful in capturing design rationale. Based on a literature review, the aim of this paper is to describe how the concept of capturing design rationale from the engineering industry and its tool called the Design Rationale Editor (DRed) can be incorporated as a new conceptual tool called the DRed-based decision-making model for use in the design stage of construction. It can capture and evaluate design rationale and hence help designers to make better and more effective design decisions through assessing and perhaps increasing the design information maturity. The definition or concept of information maturity in construction has yet to be explored and will form a major part of future work. Future work will be to demonstrate how design information rationale can be captured and edited along the life cycle in the digital environment through the use of real case studies, and to address any issues and limitations on its applications in the industry.

Keywords: design, decision-making, information assessment, maturity, modelling.

INTRODUCTION

The design process for a construction project is not linear, it is iterative; it involves many different stakeholders and is reliant upon having the right information available at the right time. A major challenge in a construction project derives from different organisations relying on a large number of various data sources that are interconnected and interrelated, yet with no proper way or tool to manage these sources in a convenient, integrated and principled way (Franklin et al., 2005). Such an information management issue can be attributed to a lack of a clear and concise understanding of

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the data or information generated and received between different stakeholders, such as designers and engineers and other construction professionals, at the conceptual design stage. This is critical to a successful project to ensure good design decisions are made at the early design stage of a project (Raisbeck and Tang, 2009), such as at the Concept Design stage (RIBA Plan of Work, 2013). These good conceptual design decisions “can demonstrate a constructive approach to planning requirements and greatly reduce the risk of costly later revisions” (RIBA 2011). In order to achieve this, it was suggested that a small increase in upfront costs of just 2% to support sustainable design can, on average, lead to a building life cycle saving in total whole life construction costs of approximately 20% (Kats, 2003). It can be seen that key decisions made at the concept design stage can generate a significant impact on the product in terms of the way it is produced and the strategy to be marketed throughout the life cycle of a construction project.

Research over the last twenty years has shown that the early development of design support systems is imperative to construction projects (Franklin et al., 2005; Kolodner, 1991; Senthilkumar et al., 2010). The systems can assist designers dealing with this massive and complex information, and can provide automated problem-solving abilities at early design stages. At the other end of the value chain, an emphasis has been placed on the provision of more accurate and high value information for building performance analysis and evaluation (Klashner and Sabet, 2006).

This paper aims to demonstrate the importance of capturing and evaluating design rationale, and how the principles of Design Rationale Editor (DRed) tool could be used to develop a DRed-based Decision-making model. This conceptual model would assess the design information maturity at the concept design stage of a construction project, and so help designers and other construction stakeholders to make optimized decisions by assessing design information’s context-sensitive characteristics and attributes. The three major research questions this paper will address are: 1) What is information maturity in a design process? 2) How possibly can it be increased through the evaluation and capture of design information rationale? 3) Why is it important to adopt this developing model in collaborative design in construction?

Research rationale

This paper is based on a literature review, where a gap was identified and developed. The literature review revealed that the deficiency of capturing design information with the characteristics of high value, high quality and, most importantly, “maturity”, results in information overload and impacts the efficiency of information management in construction. It is therefore important to assess the maturity of information used in construction. Moreover, there is a great potential for the introduction of DRed tool methodology to assist with the capture of design information rationale in construction. There is a potential for integration of this method with a decision-making model, which could assess design information maturity, and demonstrate the probability of success of each design option of design packages. It is upon this probability that optimized design decisions can be made.

In recent years, the rapidly increasing pressures of “data everywhere” creating information overload, have resulted in practitioners needing to take more interest in and put more effort into monitoring the effectiveness of their data and information management. The application of digital design tools, such as Building Information Modelling (BIM), breaks down certain information flow barriers and at the same time bridges communication between extended design and construction teams. In practice, commercial data from the UK construction sector also showed that BIM could achieve a

consistent reduction of 8-18% in the cost associated with the design stages of the RIBA Plan of Work 2013, while the upside potential of savings could be as high as 40% (BIS 2011). Moreover, there is a deficiency in generating reliable information within and across project teams, against which a mechanism for the justification (e.g. costs and benefits) of using BIM has to be provided (BuildingSMART, 2010). Unless the issues of capturing reliable information at the concept design stage are otherwise addressed, the benefits of BIM application cannot be achieved (Bernstein and Pittman, 2005).

The difficulties of retrieving high value, high quality and mature (i.e. reliable, stable, precise and complete) design information at the concept design stage are sometimes considered as a major shortcoming of existing digital design support tools. This has led to a disparity between the reality and the simulation of conceptual digital building models (Moffatt and Kohler, 2008). This deficiency is identified as one of technical reasons that hinder the adoption of digital design support tools (Bernstein and Pittman, 2005). In fact, during the design process of a construction project, the stakeholders become more subjective owing to the increasing complexity of design problems and project objectives (Nemati et al., 2002). Consequently, the ability of designers to retrieve and utilise information is critical to the project outcome in its life cycle. There is an increasing volume of design information, and if this is immature (i.e. unstable, imprecise or incorrect) (Hanssen, 1997; Helms, 2000), this can lead designers to make inappropriate design decisions, which will result in the high possibility of reworking the design, and even be fatal to a construction project. On the other hand, the provision of mature information can help designers make effective decisions with avoidance of immature information being used, increase effectiveness of information management. Therefore, it shows the need for a well-developed practical strategy for the purposeful exchange of and integration of meaning, high value, quality and mature information within the digital design environment.

DRed supports the function of mapping and modelling design as an information processing activity, which has been found to help designers view, clarify and structure their design thinking and assist with managing design tasks. The capture and evaluation of design rationale in the engineering industry using DRed has proved to be efficient in assessing design options (Bracewell et al., 2009). This technique can uncover the reasons behind selecting one option over another and allows fully-evaluated decisions. It also provides visualisation and justification of any arguments among immature design decisions, and can possibly make a significant impact on a collaborative design process..

The framework of information evaluation provides the foundation for context-sensitive information assessment (Darlington et al., 2008). This framework has identified the dimensions influencing the evaluation process and defined the elements (information object, design package); characteristics (value, quality, and in this paper, maturity); and attributes (accuracy, reliability, credibility, relevance, accessibility and so on) of information. It facilitates decisions to be made during the life cycle of information about its management, such as acquisition, storage, creation, maintenance and disposal. Moreover, it is a strategy that supports good decisions to be made concerning information in respect of its capability to satisfy the current and short-to-medium-term problem solving or need for decision-making. This strategy promises a basis for the development of an automatic and semi-automatic information maturity evaluation methods

It is a potential of the Bayesian network that it could be used to assess the information maturity of primitive tasks of the defined packages, its probability, and evaluate information maturity attributes (such as accuracy, usability, trustworthiness and so on). The network links various interrelated sub-components together, with each sub-component regarded as a node. In information management and automated design, the network can act as a probability support structure for combining the various

characteristics and metrics into an overall assessment of quality (Tang et al., 2007), and as a design support tool (Matthew, 2007).

NATURE OF INFORMATION IN CONSTRUCTION

Knowledge can be classified in various ways, Quintas' (2000) "Iceberg model" classifies knowledge as explicit, implicit and tacit. This is further explained by Tang et al. (2007), who state "knowledge can be explicit (recorded or codified in some way), implicit (in the mind) or even tacit (cannot be recorded and codified in any format). Explicit knowledge can be stored as information". This design information is uniquely designed, structured and applied to complete a task in a project by decisions made on it. Communication between designers and among stakeholders is a multidimensional flow of information, and is highly dynamic and interactive.

The stakeholders in a construction project have to retrieve relevant information from other data subjects such as colleagues, documents, drawings, models and databases. Therefore, the ability of designers to retrieve and utilise information is critical to the outcome of the project.

DESIGN PROCESS IN CONSTRUCTION

The execution of the design process aims to satisfy the design requirements, in order to achieve design quality of a building, which is a combination of functionality (how useful the facility is in achieving its purpose); impact (how well the facility creates a sense of place); and building quality (performance of the completed facility) (OGC, 2004). Given this, proactive thinking and planning of the design at concept design, in terms of how to achieve design quality, is critical to the success of any construction (OGC, 2004; Emmitt, 2007). Although the introduction of digital design tools, such as BIM, help to address the iterations of redesign in order to refine or amend the functional requirements, design concepts and financial constraints of a project, its use for information management in facilitating effective information management in the construction design process still needs some improvement.

Darlington et al. (2008) discussed the foundations of a framework for information evaluation. They also identified and defined a number of important variables, e.g. the objects of evaluation, the high-level operational contexts in which evaluation takes place, the motivations and post-evaluation actions associated with these contexts and how they and information entity attributes can be mapped on to the information life cycle. This leads to the questions about the value and quality of the design information (Tang et al., 2010) and, more importantly, the maturity of the information in order to avoid unnecessary design reiterations.

THE CONCEPT OF INFORMATION MATURITY

"Right information needs to be available at the right time in the right format to the right person" (Winch, 2002). The term 'right' strongly relates to how 'mature' the information is. There is little literature defining the maturity of information but immature information is defined as tentative, untested and possibly incorrect information (Hanssen, 1997; Helms, 2000; Grebici et al., 2006). In construction, the Lean Management Model proposed by Sacks and Goldin (2007) demonstrated that this method facilitates the replacement of a fixed activities network to be scheduled for the purpose of works' completion in a highly dynamic environment. In order to achieve this goal, the construction schedule should be carried out according to the maturity level of the client's and designer's changes to design. In the construction production phase, maturity is measured according to the state of readiness of a work package or a task (Sacks et al., 2010). Watson (1998) stated that in construction the accumulated data becomes information when it is mature enough and

ready to be passed on from one discipline to another. This information needs to be interpreted and applied by users (information creators and receivers) within the construction contexts (Darlington et al., 2008). Otherwise, immature information will flow from one stakeholder or knowledge broker to another. In this paper, mature information is simply defined as high certainty information (e.g. stable, precise and complete) that can be passed on to the next stage of the design process with the least likelihood of re-iterations and/or other associated uncertainties, which can cause significant impacts on the collaborative design process among stakeholders.

The concept of information maturity assessment for decision-making can refer to the development of a number of approaches to automatic information evaluation (Tang et al., 2007; Zhou et al., 2008). This concept includes the principled characteristics identified by the above researchers as being central to information maturity assessment, including accuracy, usability, trustworthiness (which together consist of quality), currency, benefit, impact and relevance. Such a concept takes the manifestation of “information as thing” rather than merely considering “information as knowledge”, since the identification of “information as thing” provides the foundation for considering information as practical objects for evaluation (Darlington et al., 2008). Additionally, information maturity assessment cannot be undertaken in a vacuum, which is characterized by the set of circumstances and facts around the event, for example, context. Therefore, information maturity assessment has to consider the influential and common characterized dimensions. These are the organizational, motivational and information life-cycle dimensions. The consideration of dimensional influence supports information assessment that can have the necessary context-sensitivity.

After taking into account the above, information maturity assessment for decision-making could be explained by an analogy of the “tube map”. The tube map was designed to provide the clearest information for passengers, to allow them to discover the shortest and fastest route from one stop to any other. The design process needs to be mapped in the same way, breaking down the process into a number of design packages, with the design options generated within each package assessed on the basis of their information maturity level. An optimised design decision will be made and combined with the consideration of stakeholders’ preferences, project goals and expenditure. The “tube map” concept is represented in Figure 1 which illustrates what information has been assessed in relation to its maturity level.

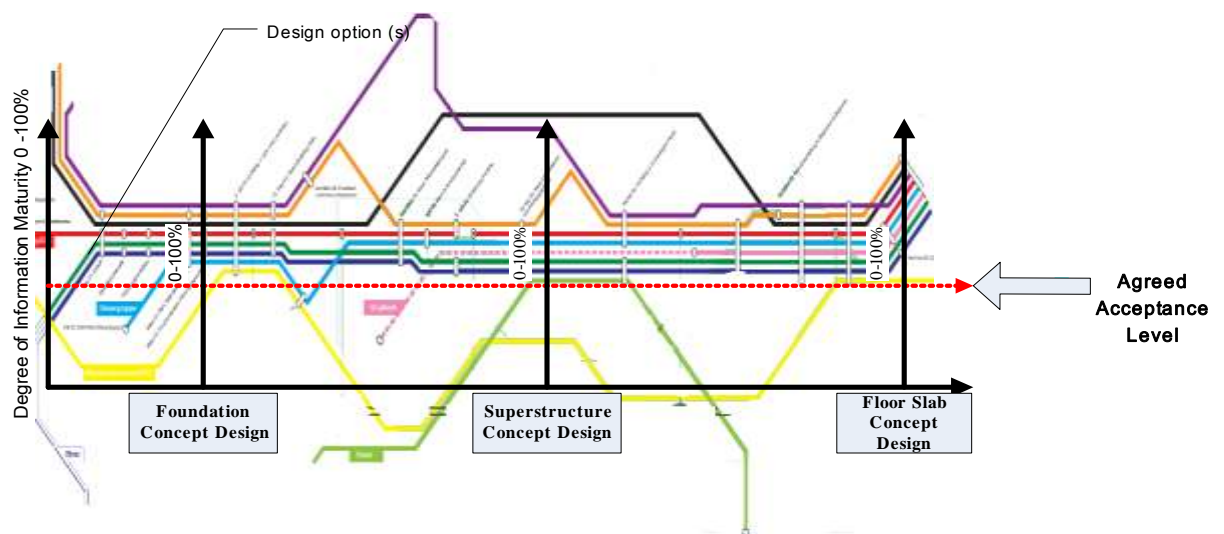


Figure 1 Presentation of "Tube map" concept for assessing information maturity in structure concept design

The x-axis in Figure 1 shows the design packages of the structure concept design, which include the foundation, superstructure and floor slab concept design decisions, while the y-axis represents the level of information maturity for each package (from 0% to 100% probability). Each coloured line represents a design option. The lines above the red dotted line (agreed acceptance level) represent the design options (orange, black and purple) with more mature information being represented towards to the right hand side of the maturity map. The travel routes, representing design options, take account of all decision-making criteria that reflect probability, certainty, uncertainty, risky and possibility issues when assessing the information maturity of multiple design options. The point where each line intersects a vertical axis represents the level of the corresponding information maturity variable of a particular design package. As defined, visualising results in this form allows the designers to identify quickly the range of the level of information maturity, the probability of the design options. For example, it can be seen that the best designs for the beam section (which include the design options: purple, orange, dark green, red and light green) have a higher volume of information maturity above the red dotted line (the agreed acceptance level). This means that the five design options meet a project's design requirement better than those with a maturity below the acceptance level. This way of visualizing information allows a quick assessment of information maturity levels. For instance, the purple best design option changes after passing through the entire Girder section, with its maturity probability decreasing. This indicates that the purple design option for the Girder has a strong influence on the design performance, due to its deficiency in meeting the design requirements. The optimised design decision option for each design package can be generated in accordance with a high level of information maturity; the final optimised design will be produced as a combination of all the best options for each package.

The benefits of assessing information maturity are 1) the expected and targeted certainty among designers and other stakeholders on different design options (uncertainties) are lined up so that mature information is provided as an input certainty for the stakeholders in the next stage of the project life cycle; and 2) a unified language for communication, for instance, the optimised design option is the one with the highest level of maturity, is interpreted by a singular language, corresponding to the highest probability. The higher the probability of information maturity, the better is the design option. An agreed acceptance level for information maturity, in other words, an acceptable probability of information maturity, is generated among the decision makers for a specific design package, for example, between the architect and the structural engineer when determining conceptual superstructure structure design. The consensus reached enables the mitigation of the probability of occurrence of arguments or conflicts that may result in design changes. Visualizing information during the design process enables the stakeholders to monitor the variation in maturity levels of the design options.

DESIGN RATIONALE EDITOR (DRED)

An advantage of accurate design maturity assessment is less re-design because the organisations can measure their designs' maturity in the process (O'Brien and Smith, 1995). A better understanding of designers' interactive processes and thinking should help to establish methods for maturity assessment which allow decision-makers and stakeholders to forecast the level of risk on releasing a design option (O'Brien and Smith, 1995). The Cambridge Engineering Design Centre carried out research into information capture, storage and retrieval for 20 years. Lee (1997) undertook a review of the advantages of the available design rationale capture tools while pioneering work can be traced back 43 years to Kunz and Rittel's research at 1970, who developed the Issue-Based Information System (IBIS). A tool called the Design Rationale Editor (DRed) has been developed to assist engineering designers to structure their design thinking, to

capture their rationale, and to reduce the need for paper work (Bracewell et al., 2009). DRed has been popularly adopted by Rolls-Royce in the design stage of production. This paper considers the use (and development) of this tool in relation to the definition of information maturity in construction. This would not only allow the capture of design rationale but could also increase the maturity of design information. The inclusion of the design rationale in the design process makes an important contribution to decision-making in respect of which design options work and which do not. The major contribution made by DRed in the engineering sector is to understand design rationale for taking design decisions by weighting multiple aspects together in the three stages of the traditional design process. It is a linear process that consists of the design task, the creation, the evaluation, and determination of design options.

DRed as a design rationale capture tool has been shown to improve the design process. The listed advantages of using DRed, include the provision of better support for re-design, learning, reuse, maintenance, documentation, project management and collaborative work (Lee, 1997). It also allows "designers to record their design rationale at the time of its generation and deliberation". Functionally, DRed can be complemented with the analysis of BIM, CAD tools, Office, web and communication applications, which designers use to support their day-to-day activities. DRed facilitates the creation of an optimised design portfolio which is structured according to the dependencies in the design rationale, through the capture and evaluation of design rationales. Such a tool with its theory/methodology can assess and then increase the final design information maturity in its routine use, which is potential to improve the design process in construction.

DEVELOPING A DRED-BASED DECISION-MAKING MODEL

The design of a new facility often begins with the search for the most relevant information for a design. In order to support collaborative design between designers, this section of the paper shows how DRed can potentially be developed as a conceptual DRed-based decision-making model to capture the design rationale of designers and hence to assess and then increase the maturity of design information in the concept design stage. Stakeholders in this stage, such as architect and engineer who will make design decisions, are both information providers and information receivers. Therefore, design decisions should be made depending on the level of information maturity (agreed acceptance level), as agreed by the stakeholders concerned (such as architect and structure engineer, in structure concept design process), which is agreed by design team and other stakeholders. By establishing a platform for communication, the developing decision-making model encourages collaborative design between actors from multiple disciplines to share their knowledge and experience about both the design process and the design content. Figure 2 shows the conceptual DRed-based decision-making model in this research and how it can be applied to construction. In this model, the design rationale is displayed in a document as a graph of nodes linked with directed arcs. The user creates the nodes by choosing from a predefined set of element types. More than just to capture design rationale, it is a model to assess design information maturity. Therefore, the key element types include design issue, answer, argument (Bracewell et al., 2009), as well as criteria, attribute, and attribute option. Questions to ask include: 1) What design rationale is worthy of capture? 2) In what form is it post capture? And 3) Once the design rationale has been identified, captured, evaluated and stored, how can it be shared with others for reuse?

As for the application of DRed, designers start on the basis of forming theories concerning the causes of the potential problems, and are keen to find out the evidence to support or refute them. DRed can be used to capture the track of this diagnostic activity during its process, and Figure 2 shows the resulting chart with the diagnosis of evaluating superstructure options by the use of a 'traffic-light coloured' system. All the elements in

the DRed chart are given a colour, which represent various statuses of the elements. For example, each superstructure design option will be judged by decision makers' knowledge and experience by manually assigning a colour in a range from red to green. An element with green colour means the designers are satisfied with the diagnosis result, which is precise, complete and correct (i.e. mature), such as in "structure system option 1" the issue "REQ for typical penetrations" as shown in Figure 2. Conversely, if an element is not satisfied by the designers, it is marked as insolvable and displayed in red, e.g. the issue of "structure cost" in Figure 2. Different design elements are interactive, but not isolated from each other. The linkage among the various design elements is established based on a Bayesian Network (BN) in order to assess their context-sensitive information attributes (such as currency, relevance and so on) within each characteristics (for example quality, value and maturity), in which each design element is regarded as a node. BN is a probability support network structure. Finally, the information maturity of design option 1 is assessed as having an A% probability.

A designer's diverse assumptions are captured and evaluated as answered elements, which will pass along the upstream routine until the issue is resolved. A successful resolution to a design issue relies on the number of answers being accepted. The higher the number, the higher is the percentage of the issues that are resolved. Hence, the maturity of that piece of design information increases until it reaches its optimised level. In the example of design option 1, if one more issue, such as "structure cost" is resolved, the information maturity of design option 1 increases to B%. This is a higher probability which shows an improvement to design option 1. The final optimized design decision needs to be determined after overall consideration of all the potential design options, relying on the assessed level of information maturity.

By visualising the design rationale, the conceptual model can: 1) monitor the design behaviour through assessment and capture immediate design thinking ; and 2) improve the 'richness and clarity' (Bracewell et al., 2009) of recorded rather than personal information, as shown in Figure 2, and hence increase the design information maturity. It helps to line up the targeted and expected certainty between designers and other stakeholders .

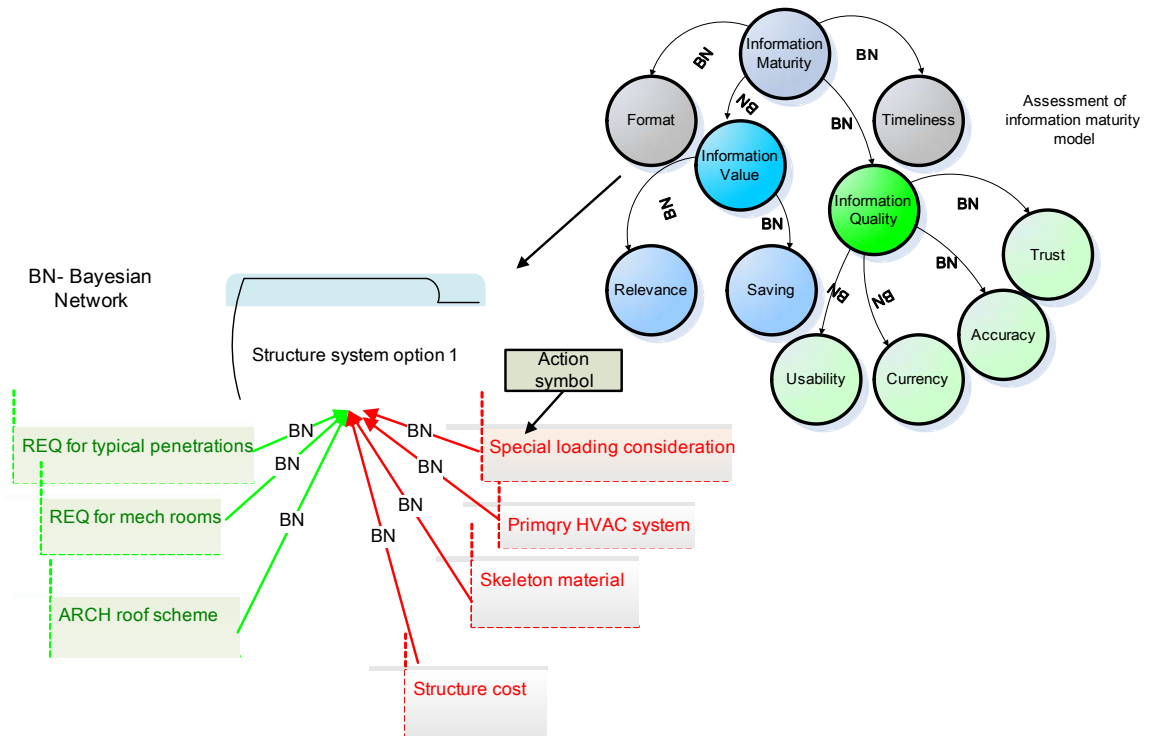


Figure 2 A demonstration of the conceptual DRed-based decision-making model for changing curtain walling system in the conceptual design stage

FUTURE WORK

The definition of design information maturity in construction has yet to be explored and will form a major part of future work. Further research is needed to demonstrate how design rationale can be captured and edited along the life cycle in digital design environment, such as a BIM environment (e.g. through the pre-construction, construction, post-construction and facility management stages), by the use of real case studies. There is a need to address any issues and limitations on its applications in the industry, in particular:

1. Which attributes of mature information in each description should be included in the model?
2. How can the measurement of future value of information maturity be carried out in construction at the conceptual design stage associated with RIBA Plan of Work Stage C?
3. How should the design rationale evaluation be carried out with multiple designers at the conceptual design stage?

Acting too early or too late can turn a good decision into a mistake. Untimely information flow has been proved to affect the quality of decision-making in a design process (Whelton and Ballard, 2002). The time scale for capturing design rationale needs to be explored further. McKenna (1994) treated this kind of decision-making model as being based on bounded rationality and suggested that it should include three investigation processes: the sequential consideration of alternatives; using heuristics to identify the most appropriate alternatives; and choosing on the basis of identifying the first acceptable solution.

CONCLUSIONS

The volume of digitised information is increasing but some of the intrinsic characteristics in the design process, e.g. value, quality and its overall maturity need further exploration. This paper shows that it is feasible to develop a collaborative DRed-based decision-making model to facilitate designers to make effective decisions in the design stage of a construction project. Such decisions will increase the productivity of a construction project design, in terms of cost, time, innovation, and sustainability, and will help to strengthen a company's competitiveness. The process of understanding the nature of information in construction will reveal that the identification of mature information (i.e. high value, high quality information, thereby minimizing the design re-iterations or other associated uncertainties) should be beneficial in bringing about optimized decisions in the design stage of a project. However, the concept of information maturity in construction has yet to be explored. In particular, when dealing with uncertainty and design changes among designers and various stakeholders, the conceptual DRed-based decision-making model could provide a systematic and informative way to show the optimised design decision through capturing and evaluating the design rationale of designers, a concept adopted from the engineering industry. In conclusion, there is a need to apply the conceptual model to construction, to be embedded in the digital working environment, and hence increase the information maturity level of design information among designers in order to facilitate effective information management.

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