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THE APPLICATION OF QUALITY FUNCTIONAL DEPLOYMENT TO MODULAR OFFSITE CONSTRUCTION PRODUCTS

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Abstract

This paper investigates requirement management practices in the construction industry, and proposes and evaluates the application of Quality Functional Deployment as a requirements analysis tool for offsite construction products. Two case studies were carried out. The first involved analysing technical documents and conducting interviews with engineers from the collaborating company to understand current requirements management practices. The second evaluates the application of QFD to a modular plant-room product. A QFD model was developed using a reverse engineering approach, which involved extracting requirements information from technical documents. The QFD model was subsequently validated by engineers from the collaborating company during a workshop. This research highlights that QFD has a strong potential as a requirements analysis tool for advanced offsite construction. This is because QFD offers a more systematic, holistic and structured approach to requirements management than current processes adopted in the industry. The novelty of this study lies in the implementation of a functional approach to QFD and how QFD has been tailored and organised to handle modular products.

Keywords: Design management, Systems Engineering (SE), Requirements, Quality functional deployment (QFD), Advanced offsite construction

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1 INTRODUCTION

The construction industry is undergoing further industrialisation (Höök, 2006; Marchesi et al., 2013). Modularisation is increasingly applied to handle product variations. At the same time investments in advanced manufacturing are growing to support greater levels of offsite construction. The drivers of this development are the need to achieve a step change in productivity and build quality as well as to harness the benefits of economies of scale (Lawson et al., 2012). This new level of industrialisation, which is still evolving, has requirements that differ from those of existing offsite construction. It is important to understand its requirements so that efficient product management systems can be developed (Pasquire and Connolly, 2002; Gilbert III et al., 2013).

Increased industrialisation necessitates robust product planning and requirements management practices. In the construction industry due to the fragmented nature of the product development process with multiple stakeholders involved, it is often challenging to capture the complex and interconnected requirements for new building projects (Gilbert III et al., 2014). In addition, the current approach to designing tend to focus on deploying functional product solutions rather than investing time in requirements analysis and tools for requirements analysis are rarely adopted. This research is concerned with supporting organisations in the construction industry to become more requirements-oriented (Fernandes et al., 2015), i.e. systematically develop new products according to the principles of validating a design solution against the requirements captured and engineered at all levels. The aim of this research is to analyse requirements management practices in the construction industry, and propose and evaluate a requirements analysis tool to support advanced offsite construction.

Quality Function Deployment (QFD) is a systematic tool for the management of product requirements associated with multiple stakeholders. QFD consists of a series of interrelated matrices. The tool can integrate with other matrix style system management tools for increased impact on construction processes. For these reasons, QFD was selected, applied and examined as a tool to support advanced offsite construction products.

Using a reverse engineering approach a QFD model of a plant-room design was developed. The plant-room requirements were derived from the analysis of CAD models, schematics and other requirements documents. The model was further validated with experts from the collaborating company and other organisations in their supply chain. The model maps product's non-functional requirements to their functional requirements and then to product sub-systems. The novelty of the model proposed in this research lies in the implementation of a functional approach to QFD and how QFD has been tailored and organised to handle the requirements of modular products for offsite construction.

2 LITERATURE REVIEW

Requirements management is the collaborative and iterative process to identify all stakeholders, elicit, negotiate, document, analyse and validate requirements (Fernandes et al., 2015). The requirements management process has been studied both in the fields of engineering design and systems engineering. In the former, the process of establishing design requirements, typically referred to as problem definition, is recognised as one of the most important steps of designing (Haik et al., 2010; Aurisicchio et al., 2013). In the latter, the focus is on how to manage the requirements of complex systems over their life-cycles (Kossiakoff et al., 2011). Over time various tools have emerged to identify, analyse, specify and model requirements. These include, for example, product design specification documents, Quality Functional Deployment, UML and SysML. These tools typically represent requirements information using lists, trees, networks and matrices (Kossiakoff et al., 2011; Aurisicchio et al., 2013).

The following sections focus on the QFD tool as it was selected for application in this research.

2.1 QFD as a requirements analysis tool

QFD is a tool to map customer requirements to technical solutions and product components using a system of matrices. QFD has been applied to support product development in a variety of industries ranging from consumer electronics to vehicles and buildings construction (Wasserman, 1993; Kahraman et al., 2006; Yeh et al., 2011; Kwong and Bai, 2013; Hadidi, 2016). The QFD tool involves incorporation of various perspectives in product development (Cohen, 1995; Akao et al., 1997; and Kwong, 2003). The first two matrices of QFD (i.e. QFD1 and QFD2) are typically used to improve the value of product planning activities. The reliance of QFD on quantitative data and its system orientation make it particularly suitable to this objective. QFD is a prominent tool for ensuring product quality and is increasingly used for modular design (Simpson et al., 2012; Borjesson and Hölttä-Otto, 2014; Hadidi, 2016). There has been significant research interest in product oriented QFD. Much research has focused on the benefits of applying QFD to analyse product requirements. These benefits include efficient, structured, comprehensive, strategic and robust analysis of requirements. QFD has the potential for further development in terms of design automation and integration with other tools (Kreng and Lee, 2004; Almannai et al., 2007). For example, research has been undertaken to integrate QFD with the Analytical Hierarchy Process (AHP), Generational Variety Index (GVI), and TRIZ (Yamashina et al., 2002; Kwong and Bai, 2003; Hölttä-Otto et al., 2008; Simpson et al., 2012).

2.2 QFD in construction

Most QFD research in construction has focused on either the application of its matrices or the development of algorithms to use it for design automation (Pheng and Yeap, 2001; Prasad et al., 2015). QFD applications in construction tend to follow the traditional implementation. This involves use of the QFD1 matrix to translate 'customer requirements' into 'technical solutions', and use of the QFD2 matrix to turn 'technical solutions' into 'product components' (Yang et al., 2003; Dikmen et al., 2005; Wikberg et al., 2011; Lim et al., 2015; Prasad et al., 2015). In general, existing QFD studies were found to lack organisational rigor and comprehensiveness in the application of the matrices. Studies often tend to focus on demonstrating the application of QFD through simple examples rather than addressing complex requirements sets. Only a few studies have moved away from the traditional QFD implementation to investigate alternative requirements modelling methods for the construction industry. Venestra's application of QFD to housebuilding, which has focused on the development of product platforms using the Generational Variety Index (GVI), captured customer requirements in the rows of the QFD matrix and product modules in its columns (Veenstra et al., 2006). Gillbert's application of QFD to temporary housing, instead, involved mapping customer requirements in the rows of the QFD matrix and non-functional requirements, constraints and functional requirements in its columns (Gillbert III et al., 2014). A further set of studies has attempted to implement a broader variety of requirements and a more rigid organisational structure of such requirements. For example, Dikemen's application of QFD has categorised different types of customer requirements but it does not cover manufacturing requirements (Dikemen's et al., 2005). Yang's application of QFD included 'building needs' together with 'customer requirements' as part of a concept to compare decision making in in-situ construction and pre-cast construction (Yang et al., 2003). The study, however, is limited to handling only customer and building needs represented on separate matrices. Armacost proposed to use the Analytical Hierarchy Process (AHP) to prioritise customer requirements. His study, focusing on industrialised housing, has considered requirements not covered in other research such as requirements for manufacturing, transportation and maintenance. However, the study focuses solely on customer requirement prioritisation and does not include the whole QFD matrix (Armacost et al., 1994).

2.3 Research gap

Overall, it was found that with a few exceptions QFD applications in construction follow the tradition approach, which distinguishes customer requirements from technical solutions and translate these into components. To increase the applicability and potential benefits of QFD to the construction industry there is a need to further investigate the QFD concept focusing non-functional and functional requirements. In particular, a functional approach to QFD is needed that allows the capture of complex requirements sets typical of the construction industry (Burge, 2007; Dai et al., 2012). This would require investigation of the organisational structure of QFD requirements to integrate various stakeholders' perspectives.

3 CURRENT APPROACH TO PLANT-ROOM DESIGN AND REQUIREMENT ANALYSIS

A case study was carried out on a modular plant-room, see Figure 1, as a platform to understand the design and requirements management practices associated with modular products in advanced offsite construction.

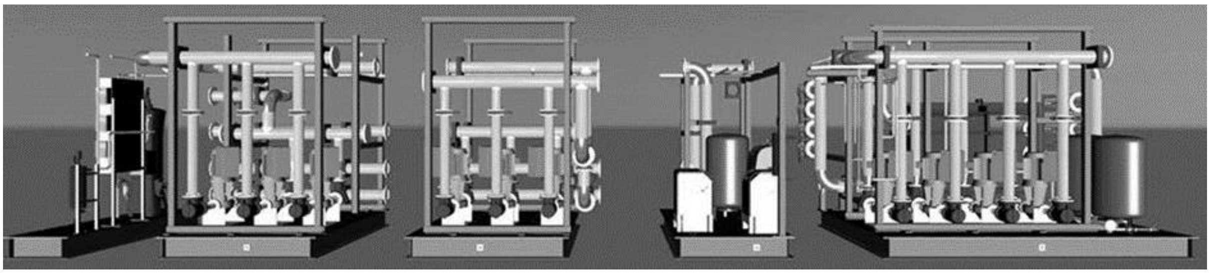

Figure 1. Modular chilled water plant-room (Source: Laing O'Rourke 2016)

3.1 Methodology

The case study involved examination of existing product documentation and discussions with engineers. Topics investigated during this study included design processes, product portfolios, and product technical issues. An extensive review of documents centred on plant-room design was performed. These documents included CAD files, schematics, bills of materials, product manuals, and requirements documentation. Fifteen informal discussions, which lasted between 15-120 min, were also carried out with different groups of engineering experts to investigate plant-room design processes and validate understanding of the collaborating company's engineering operations. These discussions took place at the collaborating company's main design offices and factories as part of periodic visits and a one week secondment. Notes were taken in all discussions and compiled into a notebook for analysis. The experts interviewed included mechanical engineers, design engineers and systems engineers who work on plant-room products. The data collected was reviewed to understand product functionality, product features, design rationale and the current design procedure.

3.2 Results: the design process and requirements management

The current method of developing plant-room designs is based on an iterative process, heavily reliant on the engineering expertise of the design team. It revolves around understanding key product features such as duties, locations and purpose of use and then developing a product schematic followed by a CAD model. To support the design process of plant-rooms the collaborating company has developed a 'step-by-step' procedure listing key considerations. The design process is carried out by internal design teams and external collaborators and it focuses on design, systems, structural and software issues.

The requirements for plant-rooms are typically attained from initial discussions with clients, consultants and experts. These requirements are oriented towards meeting specific industrial standards or client's requests rather than emphasising product functions. The requirements are listed in a requirements document covering multiple product typologies. The requirements document does not distinguish different types of requirements and it does not capture the relationships between requirements and product sub-systems. The requirements document consists of a list of items derived from initial design discussions. There is an apparent need for tools to support more effective and systematic analysis of requirements.

4 QFD IMPLEMENTATION

A case study was carried out to map the requirements for offsite construction of a plant-room using a functional approach to QFD. QFD was selected for the following reasons. First, it can capture a variety of information types including requirements, product sub-systems, and dependencies between them. In addition, it facilitates product planning and can integrate with other tools, e.g. modularisation tools. Finally, it enables quantitative analysis and justification of strategies.

4.1 Methodology

Model development: A QFD model of an industrial chilled water plant-room was developed employing a reverse engineering approach. The QFD model includes three main information types, namely *non-functional requirements, functional requirements* and *product sub-systems.* This set of information types was selected because it supports modular product development. Non-functional requirements are whole system characteristics of the product, functional requirements are the demands on product functionality, and product sub-systems are the main groups of components forming the architecture of the product (Burge, 2007). Product sub-systems and functional requirements were respectively identified and inferred by reviewing engineering documents such as CAD files and product schematics. Functional requirements and product sub-systems were subsequently mapped onto QFD 2. Non-functional requirements were identified from a deep exploration of plant-room whole systems characteristics. The non-functional requirements were then organised in a hierarchical structure according to stakeholders' demands. Non-functional requirements and functional requirements were then mapped onto QFD 1 and their relationships assigned one of three possible values (1: weak; 2: medium; and 3: strong). The weighting of the non-functional requirements was determined by an iterative process of understanding the collaborating company's objectives and those of advanced offsite construction. The outcome was then validated through a discussion with an engineer at the collaborating company. The weightings are of three possible values (1: low importance; 2: medium importance; and 3: high importance).

The weighting of QFD functional requirements and product sub-systems was calculated as per equations below: where W(Fr)x (the calculated weighting of each 'functional requirement') is determined by the product-sum of all associated non-functional requirements and their respective requirement weightings, and where W(Ps)y (the calculated weighting of each 'product sub-system') is determined by the sum-product of all associated functional requirements and their respective requirement weighting.

$$\mathrm{W(Fr)}_x = \sum(\mathrm{W(Nfr)}_y \times \mathrm{R(Fr)}_{xy}) \quad (1)$$

$$W(Ps)_y = \sum(W(Fr)_z \times R(Ps)_{yz}) \quad (2)$$

$\mathrm{W(Fr)}_x$ is the calculated weighing for the 'functional requirement' with reference number x. $\mathrm{W(Nfr)}_y$ is the assigned weighing of 'non-functional requirement' with reference number x. $\mathrm{R(Fr)}_{xy}$ is the weighting of a relationship associated with that specific functional requirement on the xy intesect. x is the reference number of a non-functional requirement sitting on the QFD1 x axis. $W(Ps)_y$ is the calculated weighting for the 'product sub-system' with reference number y. $R(Ps)_{yz}$ is the weighting of relationship associated with that specific product sub-system on that yz intersect. y is the reference number of a functional requirement sitting on the QFD1 y axis or QFD2 x axis. z is the reference number of a product sub-system siting on the QFD2 x axis.

Model evaluation: The QFD model was evaluated in two steps. First, seven interviews were conducted with experts at the collaborating company and external consultants (9 participants with engineering experiences ranging from 4.5 to 40 years). Of these interviews, five were audio-recorded and the other two were documented using hand written notes.

Second, a questionnaire survey and a workshop were conducted on the value of the QFD tool to the construction industry with participation of eight additional engineers. They were involved in the discussion on the usefulness and potential benefits of the QFD model. The questionnaire included 14 questions on the topics of accuracy of the QFD model and its potential benefits.

4.2 Results: the QFD model

A functional oriented QFD model was developed to analyse requirements for a modular plant-room. Figure 2 illustrates the overall structure of the QFD framework including QFD1 and QFD2 matrices. The QFD model consists of 40 non-functional requirements, 29 functional requirements and 18 product sub-systems. QFD1 and QFD2 include 337 and 79 relationships respectively.

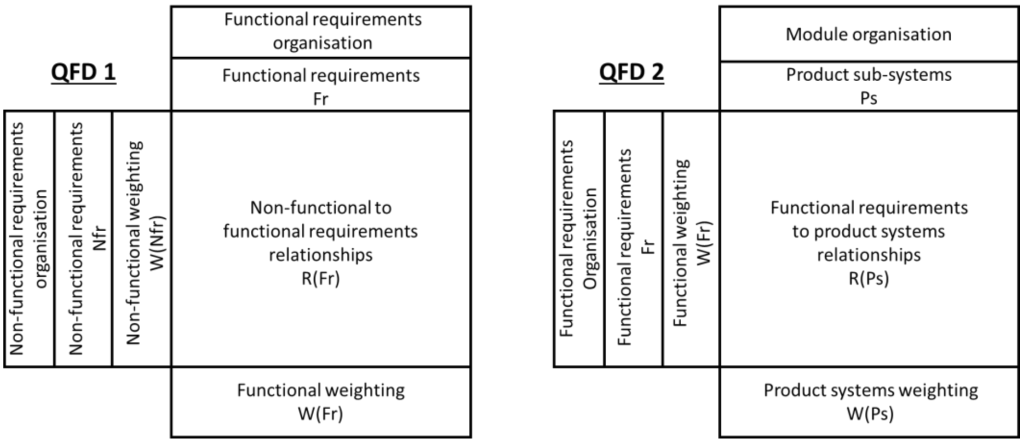

Figure 2. Overview of developed QFD model structure

Non-functional requirements (NFR): In the early stages of the product development process it is crucial that the requirements of each stakeholder are accounted for as much as possible. The plant-room non-functional requirements were organised in a hierarchal structure, which departs from the stakeholders involved (see Figure 3). The stakeholders were associated with their primary 'product viewpoints', which were then broken further down to form the individual requirements groups.

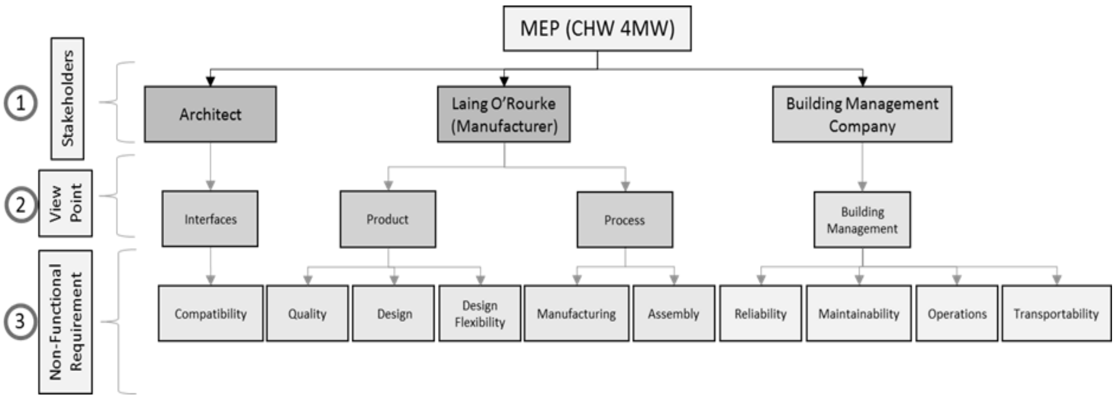

Figure 3. Hierarchical organisation of non-functional requirements

The three main stakeholders that are of significant influence for the development of the plant-room design are the architect of the building in which the plant-room will be located, the manufacturer of the plant-room and the building management company responsible for the operation of the plant-room. Figure 3 illustrates these stakeholders' viewpoints, which comprise 'interfaces', 'product', 'process' and 'building management'. Examples of non-functional requirements under the 'design' group include 'size' (target value: 3.5 m x 8 m x 3.2 m) and 'variable temperature' (target value: 6 °C to 12 °C). A further example of non-functional requirement under the 'design flexibility' group is the "degree of modularity' (targets value: 90%).

The prioritisation of the non-functional requirements was determined by their likelihood to lead to the success or failure of the product under advanced offsite construction conditions. Non-functional requirements that are specific to modular products are concerned with design flexibility, manufacturing, assembly and transportation. Among the non-functional requirements that were marked as very important there are 'unit cost', 'size', 'energy efficiency', 'compliance with regulations and standards', 'high max power', 'percentage of standard parts', 'manufacturability', 'assembly time target', 'assembly cost targets', and 'safe transportation'.

Functional requirements (FR): Functional requirements were organised into primary and secondary functions. Primary functions are those that directly target the main function of the product, i.e. deliver chilled water. Secondary functions are those that have a supporting role. Primary functions were organised into various groups, which include 'deliver cool water', 'control water temperature', 'control water pressure', 'control water flow' and 'monitor operating conditions'. Secondary functions were organised into 'protect plant-room from damage', 'ensure product integrity', 'clean water systems', 'frame components' and 'ensure system compatibility'. Some examples of functional requirements are 'cool water' (target value: 6 °C), 'depressurize water' (target value: 1-40 bar) and 'maintain operating limits' (target value: 4 MW).

According to their accumulated prioritisation weighting, the four most important functional requirement groups were 'frame components', 'monitor plant-room operations', 'protect plant-room from damage', and 'deliver cool water'. The top four functional requirements all belong to the 'frame components' group, which includes 'support plant-room spines', 'support module frame', 'support plant-room components', and 'locate spine frame'. The 'frame components' group is highly valued because of its critical role in satisfying non-functional requirements such as 'design flexibility', 'manufacturing', 'assembly' and 'transportation'.

Relationships between non-functional and functional requirements: The relationships between the two sets of requirements are extensive and their identification required significant consideration. Some examples of relationships are included in Table 1.

Table 1. Non-functional to functional requirement relationship examples

Example	Non-functional requirements	Functional requirements	Weighting
1	Variable temperature	Cool water	1
		Control water temperature	3
2	Product-building interphases	Ensure system plant-room alignment capability	3
		Secure plant-room module within building	3
3	Safe transportation for products	Prevent accidental impact damage	2
		Support plant-room spines	3
		Support module frames	3
		Support plant-room components	3
		Secure internal piping	1

Product sub-systems: The product sub-systems hierarchy was organised into 'delivery systems', 'chilling systems' and 'passive systems', see Figure 4. Examples of product sub-systems include different types of pump series, degasser systems, filters and support structures. These product sub-systems were further organised into different modules.

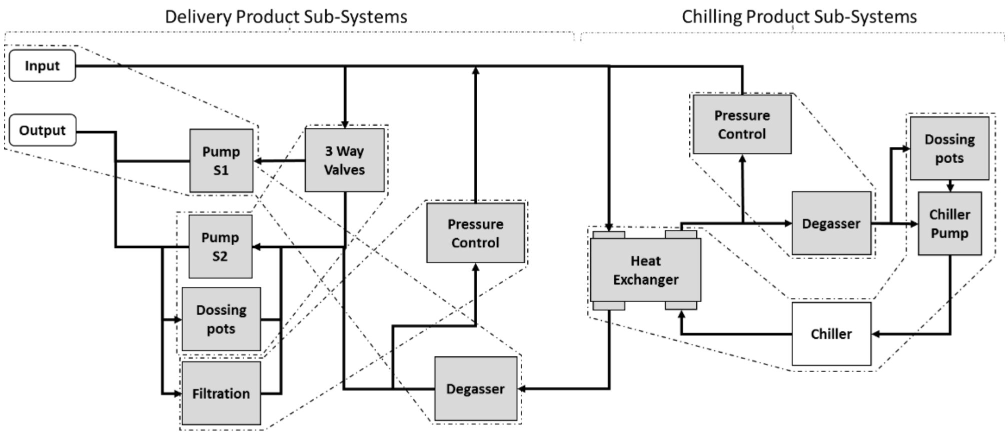

Figure 4. Simplified schematic of the chilled water plant-room

4.3 Results QFD evaluation

The QFD model was evaluated through a survey and a workshop.

4.3.1 Survey results

The survey questions covered requirements relevance, accuracy, and comprehensiveness as well as aspects of model practicality, support and usefulness, see Figure 5. In general participants showed a high level of agreement with the relevance, accuracy and comprehensiveness of the QFD elements. The accuracy and comprehensiveness of the non-functional requirements deserves a special note as various participants either took a neutral position or were in disagreement. In the field for comments of the survey form, participants stated that the QFD model was overly simplified and did not necessarily capture all necessary aspects. With respect to this issue it is important to emphasise that the QFD model was intended to represent requirements at product system level and it was not intended to include details of components design. It seems that some participants were expecting to find more information at component level than it was supposed to be in the model.

Importantly QFD was perceived as a practical tool offering support for product planning and engineering design. In addition, comparing the QFD model to the current approach to requirements management used in the collaborating company, participants felt that focusing on a single product with the requirements categories used and the QFD pro-forma is a useful step forward to acquire increased requirements management capabilities.

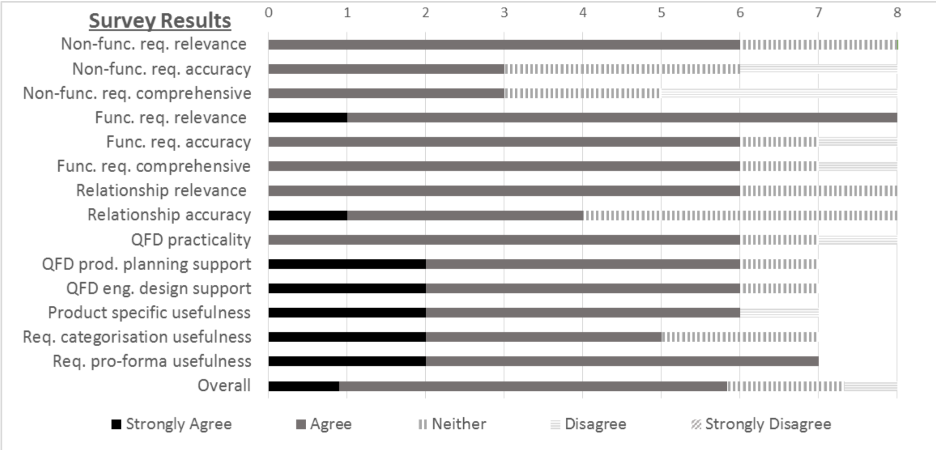

Figure 5. QFD workshop survey results

4.3.2 Workshop results

The results of the workshop show that the QFD model is in-line with the business vision of the collaborating company and has the potential to add value to its product development. The QFD tool presents a holistic perspective of the design issues associated with the development of a plant-room product. There was also confirmation that the model offers the benefit of a comprehensive and hierarchical organisation of product requirements. Participants perceived the ability to prioritise product requirements as a beneficial feature of QFD.

The results indicate that adoption of QFD in the construction industry needs to address issues such as increasing the benefits of the tool, integrating it with business operations and reducing barriers to its implementation.

Further QFD features: The QFD model developed so far does not include all known features of the tool. Further development of QFD in construction needs to give careful consideration to business competitive advantages (e.g. cost reduction) and the benefits of automated offsite construction. Hence, future QFD models have to capture requirements trade-offs and employ the concepts of prioritisation theories, weighting normalisation, and cost drivers.

Integration with business operations: The implementation of QFD would benefit from its integration with existing process guidelines such as the 'Royal Institute of British Architect' design process and V systems engineering process.

Barriers to QFD implementation: Despite the many potential benefits that QFD can bring to the construction industry, there are barriers to its implementation. First, QFD requires the gathering of a comprehensive set of requirements, which may be hard to acquire. For example, this may entail several meetings with stakeholders prior to the development of the QFD matrices, which is not a simple task in a business environment. There is also an assumption that the client and the respective stakeholders have complete and unchanging knowledge of the requirements, which may not be the case. Second, once the requirements are comprehensively collected there is the issue of interdisciplinary conflicts when organising and prioritising different requirements. Third, there is the risk of resistance to the adoption of the tool, as it conflicts with the traditional culture of flexible operations. In order for the QFD tool to be used successfully in construction, there is a need to increase support for its use.

5 DISCUSSION

This research gathered positive feedback on the application of QFD in advanced offsite construction. Previous research produced results consistent with ours but they were obtained in the context of the current stick-build and modular method of construction (Dikmen et al., 2005; Gilbert III et al., 2014). Two important findings were obtained. First, the QFD model developed in this research shows the usefulness of a functional approach to QFD with a rigorous organisation of non-functional and functional requirements and the documentation of complex relationships between them associated. The QFD model has also shown how to achieve more advanced requirements documentation and analysis capabilities compared to existing approach utilised by the collaborating company. The implementation of a functional approach to QFD and the hierarchical organisation of its elements has led to a more robust and in depth understanding of requirements (Dikmen et al., 2005). The proposed method of using QFD supports the capture of engineering experience allowing the design of next generation products to be less reliant on expert engineers. Second, the prioritisation system is a valuable feature of the QFD model as confirmed by the results of the evaluation workshop. This is because of the ability of the tool to identify issues of importance in advanced offsite construction. This feature is crucial for efficient allocation of resources and investments. This research has two main limitations. The QFD model was applied to a single modular product and its evaluation is based on a small number of engineers. To ensure more robust results further expansion on the products modelled and the sample size of participating engineers is needed.

6 CONCLUSION

This paper highlighted the potential benefits of QFD as a requirements analysis tool for advanced offsite construction. This was illustrated through a QFD model developed for a modular plant-room. The model allows for a more holistic, systematic and structured approach to requirements analysis than current practices at the collaborating company.

The model also supports a deeper understanding of advanced offsite construction requirements. Specifically, it increases understanding of how non-functional requirements, functional requirements and product sub-systems can be interconnected. It shows how product requirements and product sub-systems can be hierarchically organised. In addition, the model allows for visualisation of advanced offsite considerations especially on issues associated with manufacturing, assembly, design flexibility, and transportation.

Another important benefit of the model is its potential to increase efficiency in product planning through the application of prioritisation mechanism. This can be especially useful for the construction industry to move towards increased industrialisation and advanced offsite construction environment. The prioritisation feature of the QFD model is deemed of high value by experts and specialist engineers who participated in the study, as it can support and direct design efforts in a more efficient manner.

REFERENCES

Akao, Y. (1997), QFD: Past, present, and future. In International Symposium on QFD (Vol. 97, No. 2, pp. 1-12).

Almannai, B., Greenough, R. and Kay, J. (2008), A decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies. Robotics and Computer-Integrated Manufacturing, 24(4), pp.501-507.

Armacost, R.L., Componation, P.J., Mullens, M.A. and Swart, W.W. (1994), An AHP framework for prioritizing customer requirements in QFD: an industrialized housing application. IIE transactions, 26(4), pp.72-79.

Aurisicchio, M., Bracewell, R. and Armstrong, G. (2013), The function analysis diagram: Intended benefits and coexistence with other functional models. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 27(03), pp.249-257.

Borjesson, F. and Hölttä-Otto, K. (2014), A module generation algorithm for product architecture based on component interactions and strategic drivers. Research in Engineering Design, 25(1), pp.31-51.

Burge, S. (2007), A functional approach to quality function deployment. Systems Engineering Technical Paper, 1.

Cohen, L. (1995), Quality function deployment: how to make QFD work for you. Prentice Hall.

Dai, W., Aurisicchio, M. and Armstrong, G. (2012), August. An IBIS Based Approach for the Analysis of Non-Functional Requirements. *In ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. 591-602. American Society of Mechanical Engineers.

Dikmen, I., Birgonul, M.T. and Kiziltas, S. (2005), Strategic use of quality function deployment (QFD) in the construction industry. Building and environment, 40(2), pp.245-255.

Fernandes, J., Henriques, E., Silva, A., and Moss, M. A. (2015), Requirements change in complex technical systems: an empirical study of root causes. Research in Engineering Design, 26(1), pp.37-55.

Gilbert III, L.R., Farid, A.M. and Omar, M. (2013), An Axiomatic Design-Based Approach to Civil Engineering. *In Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering* pp. 30.

Gilbert III, L.R., Omar, M. and Farid, A.M. (2014), An integrated QFD and axiomatic design methodology for the satisfaction of temporary housing stakeholders, *In proceedings of the International Conference on Axiomatic Design 2014*, Campus de Caparica.

Hadidi, L.A. (2016), Using quality function deployment to conduct assessment for engineering designs' contractors. Architectural Engineering and Design Management, 12(3), pp.205-230.

Haik, Y., Shahin, T.M. and Sivaloganathan, S. (2010), Engineering design process. Cengage Learning.

Hölttä-Otto, K., Tang, V. and Otto, K. (2008), Analyzing module commonality for platform design using dendrograms. Research in Engineering Design, 19(2-3), pp.127-141.

Höök, M. (2006), Customer value in lean prefabrication of housing considering both construction and manufacturing, In *Proceedings of the 14th Annual Conference of the International Group for Lean Construction*, Santiago de Chile.

Kahraman, C., Ertay, T., and Büyüközkan, G. (2006), A fuzzy optimization model for QFD planning process using analytic network approach. European Journal of Operational Research, 171(2), 390-411.

Kossiakoff, A., Sweet, W.N., Seymour, S. and Biemer, S.M. (2011), Systems engineering principles and practice (Vol. 83). John Wiley & Sons.

Kreng, V.B. and Lee, T.P. (2004), QFD-based modular product design with linear integer programming—a case study. Journal of Engineering Design, 15(3), pp.261-284.

Kwong, C.K. and Bai, H. (2003), Determining the importance weights for the customer requirements in QFD using a fuzzy AHP with an extent analysis approach. Iie Transactions, 35(7), pp.619-626.

Lawson, R.M., Ogden, R.G. and Bergin, R. (2011), Application of modular construction in high-rise buildings. Journal of architectural engineering, 18(2), pp.148-154.

Lim, T.K., Jang, W.S., Choi, J.H. and Lee, D.E. (2015), Stochastic quality-cost optimization system hybridizing multi-objective genetic algorithm and quality function deployment, *Journal of Civil Engineering and Management*, 21(4), pp.407-422.

Marchesi, M., Kim, S.G. and Matt, D.T. (2013), Application of the axiomatic design approach to the design of architectural systems: a literature review, *In Proceedings of ICAD*, pp. 27-28.

Pasquire, C. L. and Connolly, G. E. (2002), Leaner construction through off-site manufacturing. In Proc. 11th Annual Conference, International Group for Lean Construction, Gramado, Brazil, pp. 263-266.

Pheng, L.S. and Yeap, L. (2001), Quality function deployment in design/build projects, *Journal of Architectural Engineering*, 7(2), pp.30-39.

Prasad, K., Zavadskas, E.K. and Chakraborty, S. (2015), A software prototype for material handling equipment selection for construction sites. Automation in Construction, 57, pp.120-131.

Simpson, T.W., Bobuk, A., Slingerland, L.A., Brennan, S., Logan, D. and Reichard, K. (2012), From user requirements to commonality specifications: an integrated approach to product family design. Research in Engineering Design, 23(2), pp.141-153.

Veenstra, V.S., Halman, J.I. and Voordijk, J.T. (2006), A methodology for developing product platforms in the specific setting of the housebuilding industry, Research in engineering design, 17(3), pp.157-173.

Wasserman, G.S. (1993), On how to prioritize design requirements during the QFD planning process. *IIE transactions*, 25(3), pp.59-65.

Wikberg, F., Ekholm, A. and Jensen, P. (2010), Configuration with architectural objects in industrialised house-building. In CIB W078 2009 pp. 341-350. Taylor & Francis Group.

Yamashina, H., Ito, T. and Kawada, H. (2002), Innovative product development process by integrating QFD and TRIZ, *International Journal of Production Research*, 40(5), pp.1031-1050.

Yang, Y.Q., Wang, S.Q., Dulaimi, M. and Low, S.P. (2003), A fuzzy quality function deployment system for buildable design decision-makings, *Automation in construction*, 12(4), pp.381-393.

Yeh, C.H., Huang, J.C. and Yu, C.K. (2011), Integration of four-phase QFD and TRIZ in product R&D: a notebook case study. *Research in Engineering Design*, 22(3), pp.125-141.

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