A DYNAMIC DESIGN MANAGEMENT SYSTEM FOR IMPROVING BUILDABILITY OF CONSTRUCTION

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For many years, improving buildability of designs, an abstract concept that is hard to be grasped by designers, has been pursued by practitioners in the construction industry. Yet, because of the fragmented nature of the industry, designers do not have the practical intuition nor the incentive for developing designs that facilitate ease of construction and economic use of resources. The adversarial culture further hinders successful collaborations between designers and constructors. System dynamics deals with the issue of how a system responds to dynamic forces thereby enabling decisions on actions to be undertaken ahead. It copes with changing circumstances surrounding a system as time passes. In view of a project organisation being regarded as a system and the factors affecting buildability of designs changing perpetually, a design management system which is operated on a continuous basis with inputs and feedbacks from contractors and other project participants ensures smooth project delivery. With the dynamic system in hand, designers with or without adequate practical knowledge and experience can constantly enrich and update themselves for improving buildability. In the long run, the incentive for developing buildable designs would be enhanced from which clients and contractors will benefit the most. By identifying the major factors affecting buildability of designs, this paper highlights the need and principles for devising a dynamic design management system for improvement of buildability. A conceptual framework for the dynamic system is built up as illustrated by an Influence Diagram.

Keywords: Buildability, Design Management, System Dynamics.

INTRODUCTION

The design stage is critical in the building development process. Design decisions affect how a building is to be built and determine the types as well as level of resources to be involved in the conversion process. Particularly, under the traditional design-bid-build procurement system, designs are usually carried out by architects and design consultants who are not the ones actually working on site (Chan et al. 2003). Problems are induced at the construction stage because of a lack of considerations of buildability / constructability in the designs.

The Construction Industry Research and Information Association (CIRIA) in the United Kingdom, defined "Buildability" as '*the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building*' (Adams 1989). On the other hand, "Constructability" refers to a wider scope of considerations including the management system employed, as the

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proponents of the term in the United States and Australia were used to quote (Wong et al. 2003). For the purpose of this paper, which focuses mainly on the design process, the term 'buildability' is used.

Designers have long been accused of deficient designs which give insufficient considerations on the difficulties likely to be encountered by the constructors during construction. The reasons behind are indeed multi-faceted. The paper aims at improving buildability of designs by identifying the factors affecting buildability for designs. In view of these factors which are dynamic in nature, the need and the principles for devising a dynamic design management system by using the methodology of System Dynamics are highlighted.

FACTORS AFFECTING BUILDABILITY

Table 1 summarises the attributes of buildability as identified by the literature. It is interesting to note quite a number of commonalities as cited by authors and researchers in different parts of the world, indicating that the issues are of global significance.

Table 1: Summary of buildability attributes

Attributes	**CIRIA (1983)**	**Griffith (1984)**	**Adams (1989)**	**Ferguson (1989)**	**CII (1987)**	**Griffith and Sidwell (1995)**	**CII Australia (1996)**	**BCA (2001)**	**CIRC (2001)**
Site	✓		✓	✓	✓				
Site Layout, Access and Environment			✓	✓	✓		✓		
Below Ground			✓	✓					
Co-ordination and Rationalisation of Design Information		✓	✓			✓	✓		
Detailing	✓	✓	✓	✓		✓		✓	
Flexibility	✓	✓							
Tools / Plant / Equipment			✓	✓	✓	✓	✓		
Use of resources / Materials, Fittings, Products and Sub-assemblies	✓	✓	✓	✓	✓	✓	✓		
Standardisation	✓		✓		✓	✓		✓	✓
Prefabrication					✓	✓		✓	✓
Innovations			✓		✓		✓		
Weather	✓		✓		✓				
Safety			✓						

Based on literature review and a series of interviews being carried out by the research team following the methodology as proposed in Wong et al. (2003), a list of factors affecting buildability has been formulated as shown in Table 2.

Table 2: Factors affecting buildability

Site-specific Factor
• Thorough site/ground investigation (e.g., bore holes, topography survey, cable detection, survey on adjacent buildings)

Site Layout, Access and Environment

- Allowing sufficient working space for labour and plant
- Enabling efficient site layout, storage and site access
- Allowing less wet trades on site
- Causing less environmental nuisance (e.g., noise, vibration, waste water, chemical waste and dust) to surroundings
- Allowing for early enclosures from weather
- Allowing for construction traffic on permanent structure early after erection (e.g., left-in steel decking on structural steel)

Below Ground

- Designing for minimum construction time below ground
- Designing for safe construction below ground
- Considering effects of below ground work on surrounding buildings, e.g., destabilising foundations

Co-ordination and Rationalisation of Design Information

- Co-ordinating drawings and specifications
- Updating specifications and removing ambiguities/misunderstandings
- Dimensional co-ordination
- Providing/facilitating combined services drawings
- Showing accurate positions for pipe sleeves and penetrations

Detailing

- Specifying tolerances for as many items as possible
- Co-ordinating tolerances specifications for interfacing items (e.g., window frame vis-à-vis window opening)
- Designing to aid visualisation of finished work
- Referring to typical/standard details for repetitive items
- Using blow up details to examine possible clashes in the design, e.g., building services clashing with reinforcements.

Flexibility

- Designing for interchangeability (e.g. left/right orientation of fittings, such as cabinets, kitchen sinks) and sub-assemblies

Tools, Plant and Equipment

- Designing for optimum use of plant and equipment
- Designing with knowledge of plant and equipment capacities
- Designing for temporary plant and equipment anchorages in permanent structure

Materials, Fittings, Products and Sub-assemblies

- Designing for locally available materials/fittings/products/sub-assemblies (including imports).
- When imported materials/fittings/products/sub-assemblies are specified, consider supply conditions (e.g., checking lead-times and foreseeable shortages)
- Specifying robust and suitable materials/components or giving directions for protecting fragile items (e.g., precast stairs)
- Designing to facilitate care and protection of completed works by contractors

Use of Resources

- Allowing use of plant and equipment available locally
- Allowing use of know-how and labour skills available locally
- Allowing economical use of labour and plant (e.g., balancing between labour and plant use to reduce overall cost)
- Avoiding as far as possible multiple handling and visits by different trades

Material Systems

- Allowing use of wide range of materials to fulfil required performance
- Giving rise to lower cutting wastages (e.g., tiles, rebars)

Installation

- Allowing easy connection/interfacing between components
- Allowing adaptation (e.g., piping around obstacles instead of penetrations) by contractor on site without extensive re-work
- Specified tolerances capable of being achieved
- Allowing easy installation without complicated fixings
- Allowing flexibility in erection/trade sequences (e.g. G/F slab laid after all upper floors)
- Allowing for early removal of temporary support to leave clear working space

Standardisation
• Uncomplicated geometry, layout and shape • Allowing modular layout of components • Allowing a high degree of standardisation and repetition • Allowing use of standard details with lots of repetitions, thereby facilitating learning curve of workers to be built up fast
Prefabrication
• Allowing prefabrication off site • Enabling the adoption of single integrated elements (e.g., whole toilet completed with sanitary ware, piping & finishes) at the discretion of contractor • Optimising the mix of offsite work (e.g., prefabrication, precasting and pre-assembly) and onsite work (e.g., final levelling and fixing)
Innovations
• Designing to allow for innovative construction techniques to be proposed by contractor • Suggesting non-obligatory construction methods for contractor to consider
Weather
• Considering possible timing to avoid carrying out structural work, external finishes, etc., during rainy/typhoon season
SAFETY
• Allowing safe sequence of trades (e.g., heavy M&E plant hoisted into position before building is fully enclosed) • Sizes and weights of materials and components are safe for workers to handle using commonly available plant

Designers are to translate client's requirements and wishes into a buildable design and usable building (Nicholson 1992). These factors affecting buildability entail thorough considerations of designers on the downstream activities. If designers have got hands-on knowledge of actual operations during construction, he / she can plan and design to adapt to the practical situations and project characteristics.

A buildable design must take into account the site constraints under the umbrella of the client's directions. In addition, careful considerations should be given as to the methodologies of constructing a building: how tools, plant and equipment are utilised; how materials and fittings are used and how products and sub-assemblies are going to be integrated, installed and detailed. Preferably, designs should facilitate the efficient use of resources during construction by allowing contractors to decide on the optimal mix of prefabricated and on-site items with uncomplicated and standardised layouts, displaying a high degree of flexibility for construction detailing, ensuring design information being correctly visualised, coordinated and rationalised and enabling a safe sequence of construction, and minimising the impact of adverse weather.

Hindrance to improving buildability

How can they be achieved? In fact, contrary to the participants' wishes, the industry has inherently posed hindrance to effect productive collaboration between designers and contractors. For example, Ma et al. (2001) have identified that there exist barriers to the implementation of constructability. Particularly, when the design stage was referred to, it was noticed that design organisations were in lack of site experience; designers and constructors did not have mutual respect to each other; constructors' input was too late to be of value and owners were reluctant to invest additional money on construction input in early days. Other obstacles to improving buildability include the highly fragmented nature of the industry; the existing culture and inertia of the industry; the adoption of normal and familiar practices by practitioners; the excessive time needed for statutory approval by government; developers' unwillingness to dedicate much efforts on improving buildability of designs; lack of motivation on the part of designers to develop buildable designs; as well as the tighter consultant fees that have recently been brought to light by interviewees during the research.

DYNAMIC NATURE OF THE BUILDABILITY FACTORS

Whilst the construction industry is still beset by an adversarial culture (CIRC 2001), and contractors and designers are reluctant to disclose information before award of contracts (Ma et al. 2001), designers who do not equip themselves with sufficient on-site experience may find it difficult to strive a balance among different project objectives including buildability.

This difficulty is due to the dynamic interaction of the factors affecting buildability. The aforementioned buildability factors are not static themselves. Two identical construction sites were found nowhere. It implies that, no matter whether we are referring to conditions below ground, site layout, the existence of any adjoining structures and the interplay of surrounding environment, a piece of land exists with its unique characteristics. Hence, different developments would have their respective features being distinct from each other, partly because of the uniqueness of individual pieces of land and partly attributable to dissimilar clients' requirements. Apart from this, things tend to change over time. New practices, techniques and skills have been developing in the wake of innovative procurement methods and advanced technologies.

IMPROVING BUILDABILITY AT THE DESIGN STAGE

The design process involves human interaction and the design outcome is a trade-off among many conflicting needs, encompassing the interpretations, perceptions and prejudices of the participants (Gray and Hughes 2001). However, a building design is sometimes only regarded as an art work (Gray and Hughes 2001), with the designers paying little attention to tackle difficulties that would confront constructors during construction. Constructors have virtually no input into the design (Bower 2003). In view of the inherent problems that resulted from late, incomplete or uncoordinated design information and designs that were difficult to build, Coles (1990) carried out a survey to identify the inadequacy of design process management. Results showed that the sources of problems are:- (i) poor briefing and communication; (ii) inadequacies in the technical knowledge of designers; and (iii) a lack of confidence in pre-planning for design works.

These problems are detrimental to the whole project teams. As such, there is an increasing awareness of the need to improve management of the design process in the construction industry with focus being put on the design deliverables (Duffy 1998). In particular, attention has been given to improving buildability of designs. For example, carrying out design-phase scheduling and reviewing of in-house design-phase constructability (or buildability) have been proposed by Glavinich (1995). A computer-aided methodology has been put forward to ease the incompatibility with other components or errors in designs as well as potential difficulties during construction, resulting from design change of a building component (Mokhtar 2000). A buildability checklist has also been developed for designers by Gray and Hughes (2001). They believed that as the complexity of construction operations is difficult to determine without extensive site experience, a design should be as simple to construct as possible. All these echo the need for tools that allow undertaking design management that accounts for and addresses the need for changing roles within the team (Austin et al. 2000).

IMPROVING BUILDABILITY OF DESIGN BY USING SYSTEM DYNAMICS

In light of the variations that exist across different projects and the hindrance to improving buildability as discussed above, static rules for optimising buildability in designs are considered inadequate. Hence, to supplement the insufficiencies of designers lacking on-site experience, and facilitate the improvement of designers on understanding their changed roles and responsibilities, a buildability database encompassing the practical and updated construction knowledge, common site practices and related legal constraints would definitely help. It should include detailed drawings and specifications, and information of tools, plant, equipment, building materials, construction technologies, methodologies and suppliers details, etc. Most importantly, undertaking a post-construction analysis would enhance constructability on similar future projects in the future (CII Australia 1996). As such, the database should allow continuous updating and interacting with project team members, especially the contractors during and after construction. This provides channels to convey feedback from contractors back to the designers.

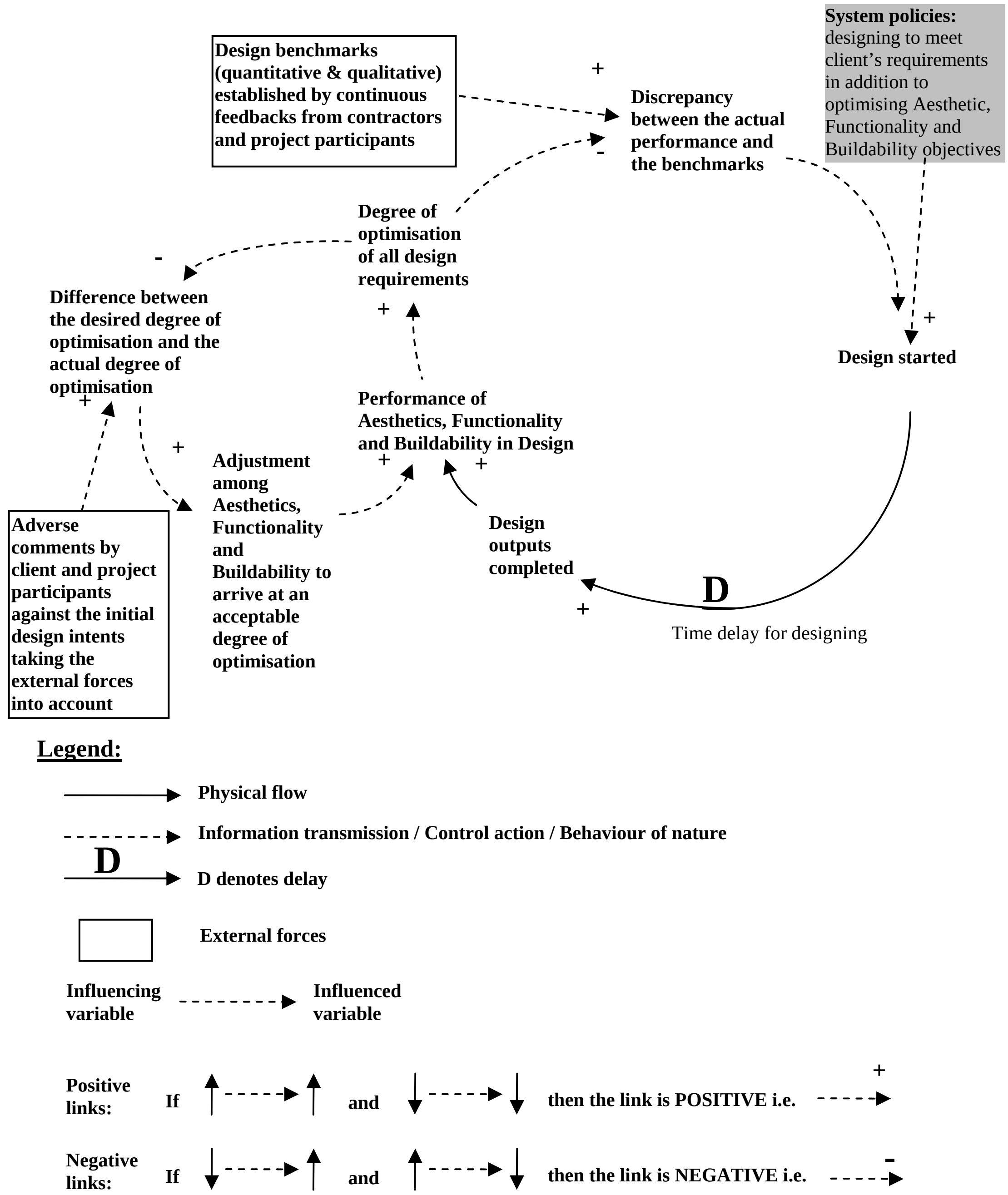
The concept of System Dynamics

System dynamics (SD) is excellent and powerful for dealing with problems which are subject to the changing circumstances as time passes, thereby enabling decisions on the actions to be taken ahead (Coyle 1996). Forrester (1961) defined SD as ‘the investigation of the information-feedback characteristics of systems and the use of models for the design of improved organisation form and guiding policy.’ where a ‘system’ can be interpreted as a collection of parts organised for a purpose (Coyle 1996). Being characterised by its multiple feedback loops to generate further actions, SD is able to fulfil certain modelling requirements, especially for large-scale construction projects (Chritamara and Ogunlana 2002). Sterman (1992) further justified that SD can be used for managing construction projects which are extremely complex, highly dynamic, and involving multiple feedback, nonlinear relationships as well as both qualitative and quantitative data.

Application of System Dynamics in design management to improve buildability

The composition of a project organisation can be viewed as a system within which different sub-systems exist and interrelate to pursue and achieve their respective identifiable goals (Love et al. 2002). One of these sub-systems can be design management. With the aid of SD, a design management system, which is operated on a continuous basis with inputs and feedbacks from contractors and other project participants, can ensure smooth project delivery. Designers, with or without adequate practical knowledge and experience, can constantly enrich and update themselves for improving buildability. Figure 1 shows the conceptual framework for design management illustrated with an Influence Diagram of SD.

Figure 1: Conceptual framework for design management with influence diagram (Adapted from Coyles 1996)



There are several points to note:

- The purpose of design management is to ensure an efficient and effective design process, whilst the client's requirements are rightly converted into design deliverables taking aesthetic, functionality and buildability into considerations.
- After a delay in designing, design deliverables are worked out based on the above requirements.
- The performance of a design can be viewed from 3 perspectives, namely aesthetics, functionality and buildability.

- To evaluate the performance of a design, qualitative assessments are used for aesthetics and functionality.
- For buildability performance, a design can be assessed by a quantification model such as the Buildable Design Appraisal System as developed and implemented in Singapore by the Building and Construction Authority (Lam 2002).
- The 3 aspects should be optimised to meet the client's requirements. The degree of optimisation of design is assessed by client and other project participants against the initial design intents taking into account the external forces.
- The external forces, which have influences on the performance of a design, include unexpected factors affecting the design, e.g., new enforcement of legislations, changes of mind by client and the emergence of different market conditions.
- Adjustments of the design contents may be necessary depending on the differences between the desired and the actual levels of optimisation.
- When the actual optimisation level meets the desired level, the design is checked against the established design benchmarks which are continuously updated with feedbacks from contractors and other project participants.

CONCLUSION

Buildability is such an abstract concept that is difficult to be grasped by designers. Whilst the ideal situation of integrated design which entails a multi-disciplinary team genuinely working at the earliest stage (Best and Valence 1999) has yet to come, it is surely more comfortable for designers to work with a feedback system which is able to supplement their inadequacy, especially for those who lack practical site experience. The authors have identified 16 groups of factors affecting buildability. Improvement towards buildability can be realised by persistently optimising the context of these factors during design. Given that the buildability factors are dynamic in nature and the requirements of buildability vary across different projects, a design management system would hence assist in adapting to the ever-changing environment. The methodology of system dynamics is used to monitor changes over time and feedbacks from the constructor and other project members. To better enhance the improvement of buildability, a buildability assessment system should also be established as an objective benchmark. In the long run, the incentive for developing buildable designs would be enhanced from which clients and contractors will benefit the most.

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REFERENCES

Adams, S. (1989) *Practical Buildability*. London: Butterworths.

Austin, S.A., Baldwin, A.N. and Steele, J.L. (2000) Integrated planning, control and improvement of building design. *In*: Augenbroe and Prins (Ed.), *Design management in the Architectural and Engineering Office,* May 2000, Ga-Tech and Delft University of Technology, 331-343.

BCA (2000) *Code of Practice on Buildable Design*. Singapore: Building and Construction Authority.

Best, R. and Valence, D.G. (1999) *Design and construction : building in value*. Oxford; Boston, Mass.: Butterworth-Heinemann.

Bower, D. ed. (2003) *Management of procurement*. London: Thomas Telford Pub.

Chan, E.H.W., Lam, P.T.I. and Wong, F.W.H. (2003) Responsibility of design for **"**Buildability**"** of construction projects. In: Ahmed, S.M., Ahmad, I. Tang, S.L. and Azhar, S (Ed.), *Second International Conference on Construction in the 21st Century (CITC-II)*, The Hong Kong Polytechnic University and Florida International University.

Chritamara, S. and Ogunlana, S.O. (2002) System dynamics modeling of design and build construction projects. *Construction Innovation*, **2**, 269-295.

Construction Industry Institute Australia (1996) *Constructability Manual.* Australia: CII Australia.

Construction Industry Institute (CII) (1987) *Guidelines for Implementing A Constructability Program*. Austin, Tex.: CII.

Construction Industry Review Committee (CIRC) (2001) *Construct for excellence: Report of the Construction Industry Review Committee.* Hong Kong.

Coles, E.J. (1990) *Design management: a study of practice in the building industry.* Ascot, Berkshire: CIOB.

Construction Industry Research and Information Association (CIRIA) (1983) *Buildability: An Assessment.* London: CIRIA Publications, special publication no. 26.

Coyle, R.G. (1996) *System dynamics modeling: a practical approach.* London: Chapman & Hall.

Duffy, A.H.B. ed. (1998) *The design productivity debate.* London; New York: Springer.

Ferguson, I. (1989) *Buildability in Practice.* London: Mitchell Publishing Company Limited.

Forrester, J.W. (1961) *Industrial dynamics*. Cambridge, Mass: M.I.T. Press.

Glavinich, Thomas E. (1995) Improving constructability during design phase. *Journal of Architectural Engineering*, June 1995, 73-76.

Gray, C. and Hughes, W. (2001) *Building design management*. Oxford: Butterworth-Heinemann.

Griffith, A. (1984) *Buildability – the Effect of Design and Management on Construction (A Case Study)*. Edinburgh: Heriot-Watt University, Department of Building.

Griffith, A and Sidwell, A.C. (1995) *Constructability in Building and Engineering Projects.* Basingstoke: Macmillan Press Ltd.

Lam, P.T.I. (2002), Buildability Assessment: The Singapore Approach, *Journal of Building and Construction Management (previously the Asia Pacific Building & Construction Management Journal*), **7**(1), 21-27.

Love, P.E.D., Holt, G.D., Shen, L.Y. and Irani, Z. (2002) Using system dynamics to better understand change and rework in construction project management systems. *International Journal of Project Management*, **20**, 425-436.

Ma, T., Lam, P.T.I. and Chan, A. (2001) A study into the barriers to the implementation of constructability in relation to project procurement process. *In*: Dr. Amarjit Singh. Honolulu (Ed.), *1st International Structural Engineering & Construction Conference,* USA: A.A. Balkema, 95-100.

Mokhtar, A. et al (2000) Collaborative planning and scheduling of interrelated design changes. *Journal of Architectural Engineering*, June 2000, 66-75.

Nicholson, M.P. ed. (1992) *Architectural management*. London; New York: E & F N Spon.

Sterman, J.D. (1992) System dynamics modeling for project management. (http://web.mit.edu/jsterman/www/SDG/project.html) (April, 2004)

Wong, F.W.H., Lam, P.T.I., Chan, E.H.W. and Shen, L.Y. (2003) An Empirical System for Scoring buildability of Design in the Hong Kong Construction Industry, in *Proceedings of the CIB Student Chapters International Symposium*, Hong Kong Polytechnic University, 26-27 Sept., 45-56.