Why interactive multi-disciplinary collaboration in building design is better than document based design

K.K. Yum
CSIRO, Manufacturing Infrastructure Technology Division, Highett, Victoria, Australia

ABSTRACT: This paper presents a theoretical framework of Interactive Multi-Disciplinary Collaboration (IMDisCo) for building design. This framework puts the whole design and communicative process into a project-based problem solving setting that is compatible to today's supply chain management framework. It also offers a set of evaluation methods based on (1) quality, and (2) cost of the design. An analysis of the framework shows that IMDisCo offers more design options than the conventional approach of document based design. With the help of suitable technology, the turn-around-time of design in IMDisCo can be shorter than the conventional approach. And thus the (theoretical) optimal design quality (cost) can be higher (lower) than the document based design. Three critical success factors for the framework have been presented. Finally, this paper discusses the future work of establishing the IMDisCo framework as an *industry* framework. In the longer term, the emerging new software that supports goal setting, design and evaluation will further enhance the paradigm shift of interactive multi-disciplinary design.

1 BACKGROUND

There has been a number of persistent issues in using Information and Communication Technologies (ICT) in the building and construction industries: (1) any rational arrangements of ICT in a project have to be reorganised in another project because project partners are different and software/hardware are all different; (2) the uses of advanced ICT in professional practice are scant and they do not sufficiently integrate with each other to present a coordinated benefit to the owner; (3) there is no incentive for the professionals to work together if they are not paid for that purpose; (4) except for the very few high profile projects (such as the National Museum Australia Project, Peters *et al.* (2001),) owners are generally not experienced enough to be able to exercise their potential and preference to seek optimal benefits from the price they have paid for the project.

With the advent of Industry Foundation Class data standard (IAI–International 2005), it is now possible to organise industry data in a standard way so that different partners, software and hardware can interpret the same piece of data with no loss of information. There are emerging advanced ICT tools that can communicate on IFC data. So the issues (1) and (2) can be resolved by adopting IFC technology. Issues (3) and (4) cannot be resolved completely via technology. They will have to be addressed from the point of view of benefit: What is in it for them to work together using common data standards like IFCs?

This paper presents a theoretical framework for interactive multi-disciplinary design. This framework puts the whole design and communicative process into a project-based problem solving setting that is compatible with today's supply chain management framework. It offers a set of qualitative evaluation methods based on (1) quality and (2) cost. It is hoped that this framework can be recognised by the construction industry, and will evolve into a stable industry framework of interactive multi-disciplinary design for various design innovations to plug in.

2 INTERACTIVE, MULTI-DISCIPLINARY COLLABORATION FRAMEWORK

The proposed Interactive, Multi-disciplinary Collaboration (IMDisCo) framework is as follows:

1 Establish collaboration structure to share goals, profits, and risks.
2 Set goals (quality, budget, time.)
3 Align processes.
4 Each discipline selects their solutions and shares critical data for design and management that affect each other's work.
5 Evaluate and coordinate solutions.

6 Repeat steps 2-5 until a satisficing, solution is agreed upon.[1]
7 Adopt the selected solution.

The framework has a few underlying assumptions. First, it is not an idealistic framework requiring people coming together to work for the common good of a project. It is the owner's benefit to drive the adoption of collaboration. The owner pays for the collaboration in which they can access and influence decision making in the design. The owner pays to control sustainability and life-cycle value. See Section 3.

Secondly, this is a collaborative framework across disciplines. Project participants are working to deliver value to the owner of the project. They share the profit and the risk. They are not in the business of pushing the risk to project partners. They share the goal of solving problems and delivering overall value to the client or the ultimate user of the building.

Thirdly, the collaboration works on a unified interpretation of a common building model. This is a technology adoption that offers productivity and efficiency.

Fourthly, the evaluation stage within each design pass is important – it decides how well the designs of various disciplines are put together to form a satisficing solution for the owner.

The following sections expand the discussion of the framework.

3 ESTABLISH COLLABORATIVE STRUCTURE

When the professional project team is working for a client, they are in fact part of the total supply chain of the client. According to Cohen & Roussel (2005), p.20, the supply chain has to collaborate to meet the following criteria: (1) aligned with the client's business strategy, (2) aligned with the client's customer needs, (3) aligned with the client's power position, and (4) adaptive. Similarly, the IMDisCo framework also requires the work strategies and structures of the professional team to meet the above criteria.

The alignment with the owner's interest is central to the organisational aspect of the construction business. It is related to procurement, contracting, and risk sharing, as opposed to *risk shedding*, according to Dawson, *et al.* (2004). This is out of the scope of this paper. For a practical example of aligning work strategies and structures with the client's strategic interest, the reader is referred to the Acton Peninsula Project Case Study (Peters, *et al.* 2001).

[1] *Satisficing*, a term coined by Herbert Simon, is a cross between 'satisfying' and 'sufficing'. It refers to the fact that when human are presented with numerous choices, we usually select the first reasonable option, rather than the best one available.

4 COLLABORATIVE WORKING

Figure 1 shows the schematic workflow and data sharing of the iterative part of the framework. The design process iteration is equivalent to the steps (2) to (6) in Section 2. Traditionally there are at least three key "stages" of design iteration:

1 Outline design – The goals focus on general approach to function, mass, space, layout, overall relationships and building performance requirements.
2 Schematic design – The goals are to work out site plan, floor plan, basic building mass, façade layout, basic materials and physical systems (structural, mechanical and electrical,) estimated construction costs.
3 Detail design – The goals focus on constructability, surface details, physical systems engineered and layout.

There can be more than one iterative passes for each of the above key design stages.

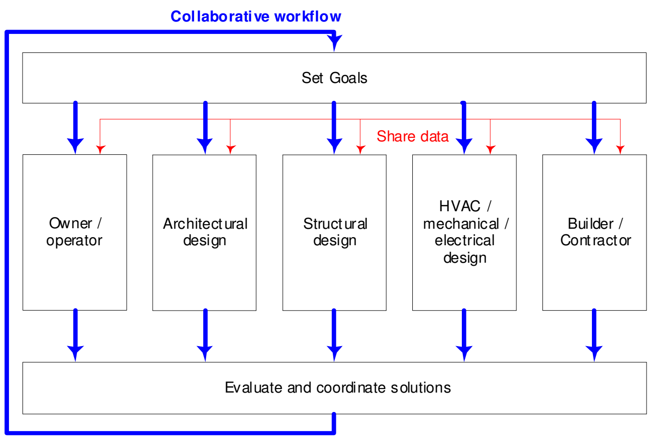

Figure 1: Collaborative workflow and data sharing

In the following subsections, the key process elements in the outline design pass will be examined through examples.

4.1 *Outline design*

According to Figure 1, the outline design stage involves many disciplines as well as the owner (the owner's representative) In this paper, we cite examples from the perspective of HVAC design to see how they work with other disciplines.

4.1.1 *Set and share goals for HVAC systems*

ASHRAE (2004), pp.11-14, lays down the following energy design goals for small office buildings:

1 Reduce load on energy-using systems.
2 Size HVAC systems for reduced loads.
3 Use more efficient systems.
4 Integrate building systems to increase energy savings potential.

These goals are recognised and shared at the beginning of the outline design stage by *all* project participants. They will work together to achieve these goals to deliver value to the client.

4.1.2 Align processes

All collaborating companies align their processes so that they chain their process and data together:

1 Select team*‡
2 Prepare owner's project requirements*
3 Select the site*
4 Define budget*
5 Prepare design and construction schedule
6 Define specific system preferences*
7 Define energy cost / efficiency program opportunities*
8 Code standard requirement / targets
9 Establish prioritised list of energy goals*

* HVAC/Energy actions.
‡ Absorbed into Section 3.

The above action list is taken from ASHRAE (2004), p.6. Actions are not particularly designed for IMDisCo framework; however, many of them can be arranged to fit into the framework. Similar aligned processes for the schematic and detail design stages can be arranged respectively.

4.1.3 Run design processes

The collaborative team (including the HVAC engineer) step through the aligned processes in Sub-section 4.1.2 to run their design; i.e. expand design goals into strategies, and select solutions from the strategy to fulfil the goals. At this stage, each discipline (architecture, Structure, HVAC, etc.) may have their own design model. They will have to integrate their outline design solutions into one at the next phase (Sub-section 4.1.4.)

4.1.4 Integrate, evaluate and coordinate solutions

The multi-disciplinary design team gets together to merge their solutions into an integrated model (Section 5.) They then run evaluation sessions (Section 6) on their integrated model and coordinate changes if necessary to produce an integrated, consistent outline model for the next stage of schematic design.

5 SHARE AND CHANGE DATA

There are three different types of data sharing in the IMDisCo framework. Firstly, the underlying model for collaborative work must be shared at the beginning of each design pass, so that all disciplines start their work on a common ground. For example, at the outset of the schematic design stage, they share the same *underlying* outline model; and at the outset of the detail design stage, they share the same *underlying* schematic model.

Secondly, within each design discipline, the designer and/or engineer can make any changes to deliver their design goals. However, in a multi-disciplinary collaborative design situation, there are changes that affect more than one discipline. This is where the idea of "interactive design" comes from. With the advent of interoperability technology and software tools (Dawson, *et al.* 2004), building design data can be changed into the (shared) building model to become readily accessible by all relevant disciplines; and the designer/engineer of these disciplines can immediately run design simulation and visualisation to determine whether such changes will have positive or negative impact on their bottom line. Simply put, the multi-disciplinary team can interact with computer programs to determine the merit of changes of design data. For example, the builder (who represents the interest of cabinetmaker and the tiler) may insist on maintaining certain dimensions of internal wall-to-wall measurements of kitchens and bathrooms so that they can use of standard sizes to save time and cost.

Thirdly, when the multi-disciplinary team start integrating, evaluating and coordinating their design solutions into a newly refined model, they will have to share the data that have formed the basis for integration. For example, the size and construction of some windows may be changed to enhance the thermal performance of a thermal zone of a building. The size of windows may have some aesthetic impacts on the building appearance. Such changes will have to be agreed by the architect and the changed data will be shared with the rest of the multi-disciplinary team.

5.1 Data type for exchange

Before running an efficient data sharing session for interactive multi-disciplinary design, data types must be prepared and organised in advance for the use of various software applications (design tools.) The efficiency is derived from the fact that the shared data of the building model from the upstream application can be interpreted correctly and used readily by the software tool downstream. The Finnish "Product Data Model in the Construction Process" Project (ProIT 2005) publishes a set of data exchange use cases, identifying the data requirements for multi-disciplinary exchange scenarios. In the domain of HVAC design, ProIT identifies the information/data type for exchange between the architect and the HVAC designer/modeler depicted in table 1.

5.2 Data standard

Given the change of clients, project partners, software and hardware between projects, the organisation of data types requires repeated definition from project to project. If there is no data standard to adhere to, the transfer of data organisation on each project will incur a penalty cost (money and time), which reduces productivity and efficiency (NIST 2004.)

The ProIT (2005) use cases map their data requirements to corresponding sets of IFC standardised data elements (IFC Aspects.) When the software tools are all developed to standardised data requirements, they will be able to correctly interpret data from upstream with little or no human intervention.

Table 1: Data type required in the Architect to HVAC engineer data exchange use case, (ProIT 2005.)

• Identification	• Logical location of building elements
• Project	• Building elements
• Site	• Building element shape
• Building	• Building element construction type
• Storey	• Building element material properties
• Space	• Special properties of building elements
• Space shape	• Equipment elements
• Project containment structure	

6 EVALUATE AND COORDINATE SOLUTIONS

Evaluation may come from inside the design team or from outside the design team. External evaluation is for the purpose of evaluating the design result completed by the design team. (See Section 7.) Internal evaluation is concerned with the evaluation from within the design process for the purpose of selecting a design solution (This section.)

Integrated design alternate solutions can be evaluated by considering the following factors: (1) Client's requirements and preferences, (2) overall quality and quality of the design of each design discipline, (3) overall cost and cost of design of each discipline.

6.1 Client's requirements and preferences

All design solutions should be able to satisfy, as much as possible, the client's requirements and preferences. Over time, the following questions will be asked and answered at the design solution evaluation session in each pass of design iteration (Figure 1.) Has the strategic position of the client been taken care of? Does the client want whole life cycle value in the design? Does each discipline offer whole life cycle value in the design option? Can the design team and members offer qualitative or quantitative measures for the fitness of their design solution to the client's requirements?

6.2 Overall quality and quality components

Peters *et al.* (2001) offer an example of how quality measures of a building should be considered. Their measures are primarily designed from the usage perspective (how good the designed building is used by the end user) (p.53.) Their measures are for external evaluation, which is different from the purpose for internal evaluation in this framework. However, the way they measure quality can be a good way for the IMDisCo framework.

For internal design solution purpose, quality measures can be broken down into the following major types:

1 Matching corporate identity and requirements
2 Meeting urban planning and sustainability requirements
3 Site, neighbourhood
4 Building, including buildability
5 Usage of building
6 Environment
7 Health and Safety

Each of the quality type can be further broken down until they are related to a design discipline. For easy referencing, the notation Q_j will be used to refer to the quality measures, where $j = 1, \ldots, n$; and n is their total number. Generally the number n can be large; however, the quality measures can be *aggregated* into corresponding disciplines, so that each (aggregated) measure has a discipline to look after it. These quality measures change from project to project; and even within the same project, they can be different from designer to designer due to personal preferences.

The overall quality is the sum of weighted measures of all quality measures Q_j, where $j = 1, \ldots, n$. As the weights can be different from project to project, it is as convenient to consider the overall quality as the tuple $Q = (Q_1, Q_2, \ldots, Q_n)$ in general discussions – weights will be added in specific projects.

There is no simple or proportional relationship between overall quality Q and quality component Q_j. Sometimes there can be adversarial relationships between qualities Q_j and Q_k ($j \neq k$). For example, in a particular building site, it is better to have a ceiling-to-floor window facing west because the opening window is facing the sea in that direction. However this site orientation may have sub-optimal effect on the thermal design as well as service life of windows. In many cases, the designers have to trade in their optimal preferences for the overall quality.

As the quality measures $(Q_1, Q_2, \ldots, Q_n)$ are dependent on the design parameters in a complex way, the collaborative team can change the parameters in the model by observing how such changes can improve individual quality measures and the overall quality. Traditionally the effect of changing one design parameter on various qualities of the building could not be readily seen or felt because it took time to make the changes (e.g., redraw all changed windows) and it took time to comprehend the effect of changes (e.g. their effect to thermal performance of building.) With the help of interactive design tools based on the same building data standard (Subsection 5.2), the effect of changing can be readily seen and computed in the computer in a matter of minutes or hours rather than days or weeks. Interactive multi-disciplinary collaborative design is now feasible.

6.3 *Overall cost and cost components*

In the area of design, cost is really cost estimation. The cost of the design is generally proportional to the quality and quantity of items/materials/systems available. The total cost also depends on the expertise of and the methods used by the cost estimator. The latter consideration is outside the scope of the paper.

The error of cost estimation is roughly inversely proportional to the detail level of design. A more detailed design reduces the probable percentage error. (Merritt & Ricketts 2000).

Each quality aspect Qj is associated with a cost Cj, where j = 1, …, n, and n is the number of qualities. Without automatic quantitative tools, it has been difficult for the designers to get the cost quickly, especially at the detail design stage. This is all possible now, thanks to the emerging automatic quantity takeoff tools and cost estimation tools running under the unifying common IFC model.

The total cost is the sum of all costs $C_1 + C_2 + \ldots + C_n$ – any overlapping costs. So C may not be equal to $C_1 + C_2 + \ldots + C_n$. For example, the cost of wall materials may be duplicated in the costs of acoustic design, thermal design, construction and sustainability considerations. It is natural to seek optimal quality Q with minimal cost C. However in the real world, higher quality is usually bought with higher price; and there is a minimal quality that is desired by the building control authority. The owner and the design team must seek for a satisficing solution, a compromise between quality and cost. For this to happen, more iterative design passes are in order.

7 IMDISCO EVALUATION (EXTERNAL)

How does the IMDisCo framework compare with the traditional document based design? From the owner/client's point of view, the following issues matter: (1) quality, (2) cost for quality, and (3) time for reporting design progress, feedback and consultation.

In order to make comparisons, it is appropriate to formulate each quality/cost measure as a function of three types of variable:

Quality $Q_j\left(i_1,\ldots i_r, p_1,\ldots p_s, o_1,\ldots o_u\right)$, and

Cost $C_j\left(i_1,\ldots i_r, p_1,\ldots p_s, o_1,\ldots o_u\right)$, where

$i_1,\ldots i_r \in Q_j Inputs$, $Q_j Inputs$ is the set of all exchange data from upstream applications as discussed in Subsection 5.1 (e.g., sizes, orientation and constructions of windows that will affect the HVAC design / performance);

$p_1,\ldots p_s \in Q_j Parameters$, $Q_j Parameters$ is the set of all intrinsic parameters for the design;

$o_1,\ldots o_u \in Q_j Outputs$, $Q_j Outputs$ is the set of all design outputs for quality measure Q_j (e.g. HVAC loads and equipment sizes.)

Due to the use of Building Information Model (BIM) technology, e.g. (Khemlani 2003.), and a common data model standard (IFC), it is possible for changing and evaluating the quality Qj value by changing design variables $i_1, \ldots, i_r$ from the upstream and the output variables $o_1, \ldots, o_u$.

7.1 *Comparison baseline: Document-Based Design*

The IMDisCo framework is compared with the conventional document-based design (DocBaD) framework.

In this paper, the DocBaD framework is assumed to have the following characteristics.

1 It adopts a *waterfall* model from design to build to operate/maintain. Design is separated from the build process. Generally the build process follows the design plan. However, if it is not possible to follow through, the build process may take its own course. In the end, design and build may have divergent results.

2 Members of the design team work on their own designs. They communicate with each other at the beginning of each design pass. Generally they work around with what they are given. They seldom, if not never, ask the upstream collaborator to make changes for their design benefits. After they have done their work, they may share their final design plans (documents) around, but they seldom share computerised data, or any other things that do not make a profit, or make them liable for lawsuits.

3 Once a design is integrated and documented and sent out, it implies certain degree of "design completeness". Changes are seldom made unless they are necessary. For the reputation of the design team and its members, consultation with the

owner and public offices (fire, police, regulatory body, etc.) is done at a relatively late stage (when design work is complete) rather than at the early stage.

7.2 IMDisCo may offer more quality and cost effective alternatives for design consideration

In the DocBaD framework, changes are slow and costly to make. Each design document of the upstream process has an unintentional dominating influence on the downstream discipline: Once a design decision is made in an upstream discipline (e.g. architecture), the downstream discipline, most likely, accepts it as a design requirement and thus restricts their design options. ((2) of Sub-section 7.2.)

Suppose i_1^*, …, i_r^* are (fixed) inputs variables from the up stream plans, then the following inequality is true for each quality aspect j, j = 1, …, n, where n is quality number (defined in Section 6.2):

$$\underset{\substack{i_1,\dots i_r \in Q_j Inputs \\ p_1,\dots p_s \in Q_j Parameters \\ o_1,\dots o_u \in Q_j Outputs}}{Max} \left\{ Q_j\left(i_1,\dots i_r, p_1,\dots p_s, o_1,\dots o_u\right) \right\}$$

$$\geq$$

$$\underset{\substack{p_1,\dots p_s \in Q_j Parameters \\ o_1,\dots o_u \in Q_j Outputs}}{Max} \left\{ Q_j\left(i_1^*,\dots i_r^*, p_1,\dots p_s, o_1,\dots o_u\right) \right\}$$

(Formula 1: quality optimisation at pre-documentation stage)

Proof: The left hand side of the inequality represents the quality optimisation of the IMDisco framework. The down stream designer can ask for changes in the up stream value i_1, …, i_r to accommodate for their quality optimisation because such request in the upstream discipline can be easily fulfilled with the help from the data sharing standard and ITC tools.

Whereas in the traditional DocBaD practice (represented by the right hand side of the inequality), the up stream inputs cannot be easily changed. Even if they can be changed, the number of variations is severely limited. For the sake of simplicity, we assume that i_1^*, …, i_r^* are inputs variables from the up stream plans; and they cannot be changed.

Therefore the range of values for optimisation for the left hand side covers the range of values on the right hand side. Hence the inequality is established.

After design decisions are made and design documentation is done, in the IMDisCo framework, all design variables (Q_jParameters and Q_jOutputs) can be changed as easily as before because the computerised building model is the documentation. However, in the DocBaD framework, the designers cannot afford too many changes in their design parameters (Q_jParameters' and Q_jOutputs') as they have been *fossilised* in documentation, not in every collaborator's computer. So we have the following containment relationships after design documentation:

Q_jParameters (in IMDisCo) $\supseteq$ Q_jParameters'(in DocBaD), and Q_jOutputs $\supseteq$ Q_jOutputs'

Therefore we have the following formula:

$$\underset{\substack{i_1,\dots i_r \in Q_j Inputs \\ p_1,\dots p_s \in Q_j Parameters \\ o_1,\dots o_u \in Q_j Outputs}}{Max} \left\{ Q_j\left(i_1,\dots i_r, p_1,\dots p_s, o_1,\dots o_u\right) \right\}$$

$$\geq$$

$$\underset{\substack{p_1,\dots p_s \in Q_j Parameters' \\ o_1,\dots o_u \in Q_j Outputs'}}{Max} \left\{ Q_j\left(i_1^*,\dots i_r^*, p_1,\dots p_s, o_1,\dots o_u\right) \right\}$$

(Formula 2: quality optimisation at post-documentation stage)

Along similar reasoning, the inequality for cost minimisation between the IMDisCo framework and the DocBaD framework can be established – with operators ≥ being replaced by ≤, *Max* being replaced by *Min*.

Formulas (1)-(2) imply that the IMDisCo framework offers more choices for quality optimisations and cost minimisation than the DocBaD framework.

In reality, quality optimisations and cost minimisation cannot be achieved due to the complex relationship between design parameters and due to the positive correlation between quality and cost.

When a downstream quality design Q_k asks its up stream design process j for changes in the output parameter Q_jOutput, this may restrict the limitation of the output range Q_jOutputs in the quality design process j and hence the validity of formulas (1)-(4) is not always true. However, in many cases, given all things are equal, it seems that IMDisCo framework does offer many more design options than the DocBaD framework does.

In summary, the final design is one that offers a satisficing overall quality Q = (Q_1, Q_2,… , Q_n) with a total cost C.

7.3 Critical success factors for IMDisCo

Currently there are few projects, if any, that are running under the IMDisCo framework. There are cultural barriers as well as technical difficulties that make people resist changing to a higher level of productivity. In order to make IMDisCo a reality, the following three critical success factors (CSFs) for the IMDisCo framework must be made available *simultaneously*:

1 The owner recognises the benefits of the IMDisCo framework and offers commercial incentives to make it happen -- *Sharing profits, sharing risks, and aligning goals*. The owner has to have an understanding of the penalty of the adversarial lowest cost tendering approach.
2 The collaborating professionals adopt data standards (such as Industry Foundation Classes, IFCs) so that *sharing data* can be readily achieved across project structures to cut down cost.
3 Advanced software design tools are available so that design solutions can be made and compared in terms of *quality* and *cost*.

CSF (1) is outside the scope of this paper as it is related to the procurement issue. However, without acknowledging the strong influence of this factor, nothing can be achieved.

The technical support for CSF (2) is available from the IAI community. For further technical details and support, the reader is referred to IAI (2005.)

Here this paper provides a summary of what software is now available for CSF (3).

Key CAD software packages are currently under gone transformation. They are gradually moving from documentation (drafting) to 3D design and performance measurement with visualisation capability, based on the integrated Building Information Model (BIM) for down stream applications. See e.g., (Khemlani 2003.)

In their promotional materials, major CAD companies emphasise smooth data transfer between their key CAD platform and their associated products (e.g. structural engineering tool, HVAC engineering tool, etc.) within their proprietary data format. In practice they cannot be consistently applied across multiple projects and teams, and there are few or no methodologies for linking them up in an integrative framework like IMDisCo. Despite impressive complexity, they generally do not support goal setting, and they do not offer explicit support for the evaluation of design option. At present, the evaluation approach of many design software tools can be regarded as *ad-hoc*.

Fisher & Kam (2002) present a report on the evaluation of the benefits of applying product data model technology in the Helsinki University of Technology Auditorium Hall 600 (HUT-600) project in Finland. The way in which product data modeling was used is, again, ad-hoc; but it is compatible with the IMDisCo framework in this paper.

Setting design goals, visualising simulations and running design iterations to select a design option offers a new design paradigm – interactive design by visualisation and by simulation. Tucker *et al.* (2003) present a case study of how their LCADesign software package was used to evaluate the life cycle performance of design options.

There will be more design tools in software to support this "set goals-design-evaluate" interactive design framework in the future.

7.4 Turn-around time

Turn-around time in this paper is defined as the time required for running a pass in the iterative design loop in Figure 1. Thus

Turn-around time =

> Goal setting time + Input-data coding and verification time + Overall design time + Coordinating solution time + Evaluating solutions time + Output solution time

Where overall design time = max of design time over all professional services working on the design (architecture, structural, building services, construction planning, etc.), as they are designing in parallel.

Turn-around time is important for the client / owner. This is roughly the time for the design team (or its leader) to finish a round of design, ready to report progress to and seek feedback from the client/owner.

Without any data collected in hand, we may compare, qualitatively through logical analysis, the turn-around time in the IMDisCo framework with that of DocBaD (Business-As-Usual) framework:

Table 2: Turn-around time for the IMDisCo framework as compared against the DocBaD framework (BAU)

Turn-around-time component	*IMDisCo time as compared with BAU*
Goal setting time	Roughly the same.
Input-data coding and verification time	Shorter, with the help from automatic data exchange / sharing.
Overall design time	Shorter with the help from software tools.
Coordinating solution time	Should be shorter based on software tools and a data exchange standard. But can take long time if more details need to be coordinated. (E.g. performing clash detection in design time instead of in construction time.)
Evaluating solutions time	Should be shorter based on software tools and a data exchange standard. But can take long time if more options are considered, and if the justifications are more objective and refined.
Output solution time	The time should be shorter with the help from software tools. Will have longer time if more details is needed to output.

According to the above analysis, given all things equal, the turn-around-time for the IMDisCo framework can be shorter than that of the DocBaD framework. However, additional turn-around-time can be spent in the IMDisCo framework to ensure higher quality in design. In either case, extra value is added to the client/owner.

8 FURTHER WORK

This paper presents the IMDisCo framework (Sections 1-6). Because the scarcity of projects that are running in the IMDisCo framework, it makes sense to conduct a logical analysis of the benefits of the framework. It appears that there are more quality and cost options in the IMDisCo framework than those of BAU; and the turn-around-time is shorter (Sec. 7.)

However, because of the lack of a collaborative culture, collaborative infrastructure and collaborative design software in the industry, it is not easy for industry partners to adopt any framework in unison. In order to make it happen, the next important step is to promote a high level framework (such as this IMDisCo framework, or similar industry roadmap) as an *industry framework*. With the support of an industry-government collaborative programme, industry partners can start introducing small pilot projects under the industry framework. Once we have projects, we can start collecting data to evaluate their performance within the industry framework, which will then prove the credibility of the approach.

In the data collection process for evaluating IMDisCo, there are several results that will be interesting:

1 How is a satisficing quality solution $Q^* = (Q_1^*, Q_2^*, \ldots Q_n^*)$ and its related cost in the IMDisCo framework compared with that in the DocBaD framework? Are they uniformly better in one framework than another?

2 for each quality measure Q_j, there is a need to establish an *explicit relationship* between Q_j and its design variables $i_1, \ldots, i_r, p_1, \ldots, p_r, o_1, \ldots, o_r$. The established relationship will enable designers to compare and evaluate quality solutions through the negotiation of design variables.

In the longer term, once the industry framework is recognised and established in the construction industry, productivity design tools will be developed to include design goal setting, design processes and evaluation processes. Once these new generational design tools are on the market, the paradigm shrift of design process will be established. At that moment, design will be just like playing today's interactive games with multiple players – each player interacts with the computer, but, in effect, they are working collaboratively with other human players in a digital collaborative environment.

The final goal of these tools is to enable the delivery of a complex integrated solution accurately, quickly, and cost effectively.

ACKNOWLEDGMENTS

Thanks to the following persons who provide inputs, comments and criticisms to help make this paper more readable than its first draft: John Mitchell (CQR P/L), Robin Drogemuller (CSIRO), Gil Arnold (Planned Practice), Bilal Succar (Change Agents) and Anthony Perks (Connell Wagner.)

REFERENCES

ASHRAE 2004. *Advanced Energy Design Guide for Small Office Buildings*. Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

Cohen, S and Roussel, J. 2005. Strategic Supply Chain Management: The Five Disciplines for Top Performance. New York: McGraw Hill.

Dawson, T., Yum, K.-K., Hund, M., Plume, J., Arnold, G., Amor, R. 2004. *Technology Roadmap for Virtual Prototyping in the Australian Building Construction Industry*. International Alliance for Interoperability, Australasia Chapter. http://www.cwic.org.au.

Fischer, M. and Kam, C. 2002 *PM4D Final Report*. Stanford University, CIFE Technical Report 143.

IAI-International 2005. http://www.iai-international.org.

Khemlani, L. 2003. *Should We BIM? Pushing the State of the Art in AEC*. Available on http://cadence.advanstar.com/2003/0603/coverstory0603c.html.

Merrritt, F.S. and Ricketts, J.T. 2000. *Building Design and Construction Handbook*. 6th Edition. McGraw-Hill Professional.

NIST 2004. *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*. NIST report NIST GCR 04-867. Available on: http://www.bfrl.nist.gov/oae/publications/gcrs/04867.pdf.

ProIT 2005. *Data Exchange Use Cases* http://www.vtt.fi/rte/cmp/projects/proit_eng/indexe.htm

Peters, R., Walker, D., and Hampson, K. 2001. *Case Study of the Acton Peninsula Development, Part A Project Alliancing on Acton Peninsula Project*. http://www.industry.gov.au/assets/documents/itrinternet/MuseumConstructionPartA.pdf

Tucker, S.N., Ambrose, M.D., Johnston, D.R., Newton, P.W., Seo, S. and Jones, D.G. 2003. *LCADESIGN: An integrated approach to automatic eco-efficiency assessment of commercial buildings*. CIB W78 proceedings 2003. Construction IT Bridging the Distance. ISBN 0-908689-71-3. CIB Publication 284.