Designing Out Waste in High-Rise Residential Buildings : Analysis of Precasting and Methods and Traditional Construction

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ABSTRACT : The Construction industry is a major generator of waste material. Construction waste should be minimized at source. If we are to significantly reduce the level of construction waste designers should consider reducing construction waste during the design process. The majority of construction waste is generated from the concreting process. In general, any reduction in on-site concreting leads to waste reduction. Precasting and prefabrication therefore offers significant opportunities for the reduction of waste. If precasting is adopted there are significant implications for the design phase of the project. Additional information is needed by design staff, construction expertise is required as part of the design process. This paper shows how information modeling and Design Structure Matrix, (DSM), techniques enable designers to model and understand the implications of such decisions within the detailed design process.

Keywords : Construction, Construction Waste, Precasting, Information Modelling

INTRODUCTION

The construction industry has always been a major producer of material waste. In Hong Kong, like most developed countries, construction waste has posed an important environmental issue. The construction industry in Hong Kong generates a huge quantity of Construction and Demolition, (C&D), waste. In 2000 this amounted to 37,690 tonnes of waste per day, of which 80% was transported to public filling areas for reclamation and the remaining 20% was disposed at landfills. Hong Kong will soon be running out of both landfill spaces and public filling areas, (C.S. Poon et al, 2004) and to help reduce construction waste the Hong Kong SAR government has recently introduced waste disposal charges.

There is currently a call for the construction industry to look for new ways of avoiding, minimizing, reusing, recycling and handling C&D waste. (Alarcon, et al. 1997, Coventry et al., 1998, 2001)The Construction for Excellence Report of the Construction Industry Review Committee, (2001), recommended that construction waste should be minimized at source. This recognizes that if we are to significantly reduce the level of construction waste designers should consider waste reduction early in the design stage and throughout the design of a construction project.

Whilst construction waste is produced from a range of construction activities not all activities produce the same amount of construction waste. The majority of waste found on traditional construction projects is generated from the concreting process and the associated wet trade, which constitutes over 80% of the construction waste produced. (HK Polytechnic University & HK Construction Assoc. Ltd. 1993) Concrete waste is generated mainly from both the direct work, steel from the cutting of reinforcement bars, surplus or spilled concrete etc. and the temporary works needed for construction: timber boards from formwork and false work; bamboo from scaffolding; etc. Re-work, the need to replace, remove or extend work previously considered completed also results in construction waste. One way of reducing construction waste is by Precasting.

Precast construction in buildings includes precast concrete frames, precast flooring units and other components such as walls, floors, stairs and lift towers. More recent developments have focused on volumetric components, e.g. bathroom and kitchen modules which, used non-structurally, can be laden onto the floor slab as the structure is erected.

Precasting is considered to be an effective means to reduce the construction waste produced at site and is frequently recommended to replace cast-in-situ concrete wherever possible. This paper studies the potential of applying precast technique to minimize the level of construction waste produced at site and describes research carried out to investigate how techniques such as the modelling of information requirements, the Design Structure Matrix(DSM) technique, and other related methods may be used to evaluate the outcomes of design decisions. We conclude that the use of generic information models and the DSM technique can benefit the management of the design process for precast design in high-rise residential buildings and that these techniques can be used to evaluate design decisions and their impact on the level of construction waste produced.

2. Types of Construction Waste

Construction waste may be considered as the difference between the materials ordered and those placed or fixed on building projects, (Skoyles, E.R. and Skoyles, J.R 1987). It is important to distinguish between physical losses and monetary losses; under certain circumstances it may be cheaper to waste material than to attempt to prevent it. More importantly to examine the physical loss alone considerably understates the problem. Skoyles, E.R & Skoyles, J.R, (1987), classify material construction waste as natural waste, (unavoidable waste allowed for in the tender), indirect waste, (material used for purposes other than that for which it was ordered), and direct waste, (material which is encountered for). All these categories may to be examined when considering the impact of design decisions. This is not however the only way to view construction waste.

When construction waste is viewed from an environmental perspective a different type of categorisation must be considered. Lemaire et al, (2005), in their paper describing the development of a decision and tool to choose building products by reviewing their environmental and health characteristics consider both environmental impact categories and health impact categories. The environmental criteria include the consideration of solid waste. This is divided into four categories: hazardous waste production; non-hazardous waste production; inert waste production; and radioactive waste production.

The research undertaken by the writers and described in this paper focuses on the reduction of non-hazardous, inert, construction waste. Whilst not excluding indirect waste primary consideration is given to direct waste. No consideration is given to indirect waste that results from the wasted time of construction professionals within the design and construction process. This is not to ignore this important aspect, but rather to focus on the prime determinants of waste generation, the direct waste elements.

3. Precast Technique

Precasting moves the construction process from on-site to factory production off-site and can reduce the construction waste produced on site. (C.S. Poon et al, 2001) Precasting techniques are highly applicable in high-rise buildings of standard and repetitive design, which is common in all Metropolitan cities like Hong Kong. The Hong Kong Housing Authority of the Hong Kong SAR has been actively promoting the use of precast elements such as external facades, staircases, bathrooms, etc. in recent years. This promotion has included permission for developers who adopt prefabrication to be allocated more buildable areas in that private property developments. (Chiang Y.H. and Lok K.L., 2005)

Precasting requires a multi-disciplinary approach to design. Successful implementation of these techniques relies on careful planning & good coordination among different disciplines including architects, engineers, general contractors and specialist precast concrete subcontractors throughout the design phase. Because of the necessary lead-time to allow the factories to set up the precast elements the decision to precast is an important decision that needs to be made early within the design process. In the planning stage, precast design should be adopted as early as possible in the preliminary design so as to allow for factory set-up. The organization responsible for the Precasting should be involved in early design stage to ensure practicality in design and facilitate ease of production of precast elements in factory. During feasibility study the capacity of the existing transport system should be checked to ensure it is adequate for the transportation of precast elements and there is sufficient storage space on site upon delivery. If site area is limited, off-site storage can be considered and extra cost should be allowed for storage and delivery of precast elements. The capacity of cranes, hoists and gantries when used also as lifting machines for precast elements must be designed to cater for future installation and minimize cost of operation and damage during handling of precast components. Proper planning of erection of precast elements and the overall construction process must be established at early design stage. The precast components must be designed in erection sequence together with overall construction process. Sufficient tolerance should be allowed for manufacturing & erection. Mock-up samples should be set up to determine product characteristics and quality. Off-site and on-site testing should be carried out to ensure compliance and standard. Most important of all, last minute changes in design should be avoided as these inevitably result in expensive changes to both existing and new pre-cast units. (C.S. Poon et al, 2001, HK Housing Authority *2005*)

In the detailed design, precast building components should be designed as integral elements of the overall building design. Building services systems should be integrated with the pre-cast elements. Pre-cast elements such as external wall panels, internal wall panels can be prefabricated with openings to allow for the running of building services e.g. water pipes, conduits, etc. Penetration through precast elements must be treated to comply with Fire Services Regulations e.g. install fire collars to the openings through floor slabs. Building finishes such as floor and wall tiles can be added in factory production facility. The locations and numbers of architectural joints should match the alignment of precast elements. Recess joints are recommended for interfaces between different pre-cast components and in-situ concrete to disguise misalignment of joints. Different finishes are introduced at interface between different precast components, or with in-situ concrete, to prevent easy detection of misalignment of tile joints. Architectural joints should also be designed to integrate with structural design of joints. Self--ventilation within these joints is recommended. (Ferguson et. al 1995, HK Housing Authority, 2000)

4. Advantages and disadvantages of precast technique

4.1 Advantages of Precast Technique

As the construction process is carried out off site, precasting has several advantages over conventional cast-in-situ methods. Removal of the concreting process from site reduces labour intensive activities on site and provides a safer working environment. In-situ construction of areas with extensive amounts of architectural shape & profile are minimized. Less construction waste will be produced. Finishes e.g. tiles can be affixed in factories providing a cleaner, safer setting for tiling work that results in stronger bonds and less tile wastage. Precasting produces components of consistent quality and standards thereby better quality can be ensured. This reduces the occurrence of construction waste resulting from non-standard works and re-work. Removal of in-situ construction activities from the critical path of the overall construction process renders the construction progress less dependent on weather. The construction process can be speeded up by the mass production of precast components in factories. (C.S. Poon et al, 2000, C.S. Poon et al, 2001, HK Housing Authority, 2000)

Designers from different disciplines can work closely together in the early design stage to help to reduce abortive work. For example: in building services design, openings and routing spaces for building services can be preformed within precast elements, which also minimizes in-situ construction of areas with extensive amount of M&E installations and helps to reduce construction waste. Although the initial setting up cost is higher than cast-in-situ construction, precasting can be carried out in countries who have both developed precast techniques and cheaper labour costs. This can result in significant reductions in production cost. Fast track procurement methods can also be exploited.

Precasting can upgrade skills and techniques, enhance construction safety and encourage construction industry to reduce construction waste through innovative design. Reductions in waste and environmental merits also result through using less timber formwork, less wet trades being carried out on site, resulting in less water pollution, less noise nuisance being generated from reduced construction activities and other overall improvements in waste management as well as waste disposal. (C.S. Poon et al, 2000, 2001, & 2004; HK Housing Authority, 2000)

4.2 Disadvantages of precast technique

Precasting also has limitations. It requires longer lead-in time in the design and production processes and longer approval procedures are also normally required. Higher investment cost is imposed on contractors and precasters especially when there is an insufficient volume of work to sustain running costs and/or frequent changes of design. Precasting is not cost effective for small projects because the extra cost of manufacturing the mouldings cannot be recovered on a satisfactory unit cost basis. There may also quality control and procurement problems if the precast units are not fabricated locally but internationally.

It is difficult to control products especially manufactured outside of Hong Kong. Manufacturers can be required to produce product certificate. Quality control on waterproofing work has to be carried out off-site particularly at the interface of precast components and with in-situ elements. Supervision has to be carried out periodically off-site which may be costing especially outside the country. Precasting is not suitable for small construction sites as a larger site area than normal is required for storage of the units and maneuvering of handling vehicles. This is obviously a problem in major urban environments. Off-site storage space is required if the construction site area is not sufficient for storage. This results in an additional overhead cost. Areas for the storage of units must be hard and level and may need strengthening to enable the units to be safely stored and easily handled.

Mis-match of cast-in conduits/pipes between precast components and adjoining slab can happen. Special design is required to treat the mis-alignment of the line of finishes within adjoining precast panels and with cast-in-situ building elements.

Protection to precast elements is required during transportation and storage. Protection of precast and fully furbished units e.g. bathroom and kitchen from damages by on-going site work is required after installation. Good logistic systems are required to trace and mark to identify different parts of precast components. This is an extra cost. Special equipment may be required e.g. lifting beam, crane, lifting hooks. Such equipment may need specially trained persons to operate and incur extra labour costs. (C.S. Poon et al, 2000, 2001 & 2004; HK Housing Authority, 2000)

Cost Analysis

According to an unpublished report of Housing Authority the cost of precast techniques includes (Hong Kong Housing Authority, 2000): Material Cost which includes raw materials, moulds/ formwork, cast in items and finishes; Manufacturing Cost which includes labour, concrete curing, quality control/ supervision and mock-up;
Storage Cost incurred by additional land taken up by on or off site storage; Off-site & On-site Inspection and Testing Cost; Transportation Cost including delivery and protection; and Installation Cost, which should include cost for special lifting provisions e.g. hoist and cranes.

Based on the comparision of structural components: slab, staircase, external walls and partition walls, the cost difference between the precast and conventional cast-in-situ method ranges from 25% to 35%. However the cost of precasting can be more competitive when the following factors are considered:

- There is an overall manpower saving of 30% in productivity in precast resulting in less labour cost due to reduction of site supervision staff on site.
- Precasting results in saving in wooden formwork, cement, plastering, stone, sand, steel, timber.
- Saving in scaffolding and gondola provisions if façade units have been pre-finished at factories.
- There can be substantial saving in concrete and reinforcement for precast work due to the elimination of concrete dumping on site and optimized use of reinforcement in mass factory production. In precast floor slab, there are 28% & 45% savings over conventional in-situ construction for concrete quantity and steel quantity respectively whilst 60% & 65% respectively for precast pre-stressed concrete beams.

The cost difference can be adjusted to about 3% to 5% when the analysis of the cost difference between precast technique and conventional cast-in-situ method is based on the total construction cost.

5. Design Process in High-rise residential Buildings

The research reported in this paper compares the design process of a high-rise residential building using precast design with that used for conventional cast-in-situ construction methods. A detailed study on the design process of high-rise residential buildings has already been reported in a previous paper “Modelling Designers’ Information Requirements to Reduce Waste in Repetitive High rise Building Construction, 2005” by Baldwin et al., (2005). The paper describes the design process for the New Harmony Residential Blocks commonly found in Hong Kong public housing projects.

Like other development projects the design process for the New Harmony Blocks built by Hong Kong Housing Authority is usually divided into the following stages:

a) Work Stage 1- Site Inception and Acceptance
b) Work Stage 2- Feasibility Study and Conceptual layout
c) Work Stage 3- Master Layout and Project Budget
d) Work Stage 4- Detail Design and Specification

For each new project working manuals, instructions and guidelines are written for project staff to follow from the inception stage to the construction stage. A Master Flowchart is incorporated for the ease of reference. Periodic and ad-hoc project team meetings are convened from time to time and with client whenever necessary. Review forums will be normally conducted at strategic points in the design process to approve and review project details. The design process is managed from mainly an overview level. The focus is on design deliverables. (Figure 1 shows a typical Master Flowchart.)

There are actually many activities happening within the simple flowchart shown: information is being collected and exchanged, input of information being transformed into output which may also become information input of another activities, communication across disciplines, etc. The project duration can be compressed if information exchange can be identified, interdisciplinary communication being taken into account and activities managed to be overlapped or even re-arranged in sequence. No specific software design planning software other than those normally available for desktop use are currently adopted by the design team.

6. Modelling the Design Process by using the Design Structure Matrix (DSM)

The authors have modeled the design process using IDEF diagrams and information modeling methods. A methodology known as the analytical design planning technique, (ADePT), has been used to review the design process of a high-rise residential development of the New Harmony type. This technique which is based on a Generic Process Model for the Detailed Design Process and a technique known as the Design Structure matrix, (DSM), (S. Austin et al, 1999, 2002 & 2004, Sandukull et al, 2005, Maheswari et al, 2005) was used. First the Generic Design Process Model was amended to provide a model of the detailed design phase of the New Harmony building. This was achieved by reviewing the generic model with Housing Authority design staff and deleting redundant information flows followed by the addition of additional information requirements. This was examined against other similar projects to produce a validated model.

Analysis of the HB (1) model

The design process of the first New Harmony Block is similar to a general building development project. From Diagram 1 it is evident that the 7 tasks with the greatest number of outputs identified in the matrix of NHB (1) are:

- A.1.3.1.2 Ground floor setting out GAs
- A.1.3.1.3 Upper floor setting out GAs
- A.1.3.2.3 Upper floor spatial co-ordination GAs
- A.1.3.4.1 Building section GAs
- A.1.5.1 Internal wall layout-types, etc.
- A.1.12 Finishes schedule
- A.2.2.1 Survey work design

These 7 tasks are all Architectural Design tasks indicating that Architectural Design is the dominating design task on which other design disciplines depend. Like many other projects using cast-in-situ method, architectural design comes in the first stage in the design process. Any change in the Architectural Design will create rework or even abortive works. Ambiguous and changing instructions from client will cause confusion and result in rework or abortive work.

Further analysis of the matrix shows that civil engineering design has the least dependency on architectural design. This which can be explained by the fact that civil engineering works involve mainly external work and are less affected by the changes in the design of the building. Building services design has the greatest dependency on architectural design as building services installations are designed to fit into the building layout.

The ADePT technique was applied to investigate opportunities for improving design efficiency through optimization. After optimizing NHB (1), a new model NHB (1) _OPT was formed. (This is shown in Diagram 2) The size of the iterative loop is reduced form 104 design tasks to a main loop of 46 design tasks. The sequence of the tasks is re-arranged. Building design is a multi-disciplinary process involving exchange of information. Optimization requires different disciplines to work together in the design process.

Row number 12 of the matrix shows that cladding design has to be considered early in the design stage. Architectural design requires considerable information input from other disciplines to achieve an effective design process. The Architect has to work along with the Civil Engineer, Structural Engineer and Building Services Engineer in the detailed design as indicated in row no. 32 to 62. If different disciplines can work together efficiently and effectively in the early Architectural Design stage providing clear and accurate information, the time wasted in re-work or even abortive work may be greatly minimized.

7. Modification to the Generic Building Design Model (Summary) for precast technique

Based on the analysis on precast technique in section 2.0 above, the Generic Building Design Model (Summary) for cast-in-situ method was modified to analyse the differences in the detailed design process when precasting techniques are adopted.

Consultation with designers confirmed that the following additional information is required: (This analysis when completed formed the new model NHB (5))

a) A.0 External information requirements: feasibility report from precaster
b) A.0 External information requirements: capacity of transport system
c) A.1.13.4 On-site storage for precast elements

d) A.1.13.5 Mock-up for precast concrete elements
e) A.3.3.3.1 Precast external wall panels design information
f) A.3.3.3.2 Precast floor slab design information
g) A.3.3.3.3 Precast staircase design information
h) A.3.3.3.4 Precast kitchen design information
i) A.3.3.3.5 Precast bathroom design information
j) A.3.3.3.6 Assembling details of precast elements

In addition the design task A.3.3.2.4.2 Precast Floor Slab Design under the section A.3.3.2.4 Structural Floor Slabs Design was deleted. A new section A.3.3.3 Precast Concrete Structural Design is set up in NHB (5), which includes sub-design tasks A.3.3.1 Precast External Wall Panels Design, A.3.3.3.2 Precast Floor Slabs Design, A.3.3.3.3 Precast Staircase Design, A.3.3.3.4 Precast Kitchen Design, A.3.3.3.5 Precast Bathroom Design and A.3.3.3.6 Assembling Details of Precast Elements. In the design for precast floors, we refer to A.3.3.3.2 Precast Floor Slabs Design in NHB (5) instead of A.3.3.2.4.2 Precast Floor Slab Design in NHB (1).

8. Analysis and discussion on the New Design Process for Precast Concrete

The NHB (5) model in Diagram 3 shows the design process of a high-rise residential building that has adopted precast technique. The 8 tasks of the greatest number of outputs identified are:

a) A.0 External inputs to design
b) A 1.2 Site layout plan
c) A.1.3.1.2 Ground floor setting out plan
d) A.1.3.1.3 Upper floor setting out plan
e) A.1.3.2.3 Upper floor spatial coordination G.A.
f) A.3.3.3.2 Precast floor slab design
g) A.3.3.3.4 Precast staircase design
h) A.3.3.3.6 Assembling details of precast elements

A.0 External inputs to design has the greatest number of 56 outputs. The Feasibility Report from precaster and capacity of transport system are important external criteria for precast design. Four of the tasks are architectural design tasks and the remaining 3 are structural indicating their role of dual importance play in precast design. Architects have to work in partnership with structural engineers in design process. The role played by structural engineer is more dominating in precast design as compared to cast-in-situ design. The model also shows that information requirements A.3.3.3.2 Precast Floor Slab Design and A.3.3.3.4 Precast Staircase design are the more dominating elements in precast design as they are input information to more design tasks than other precast elements, such as precast bathroom.

The ADePT technique can be applied here to increase design efficiency through optimization. After optimizing NHB (5)_LL, NHB (5)_LL_OPT is formed. The size of the iteration loop in NHB (5)_LL_OPT is reduced from 82 design tasks to 58. Precast design is a multi-disciplinary process involving exchange of information and different design disciplines working closely together. Structural design and design of building services that are associated with precast elements are brought forward in design sequence. For example, design of precast floor slab and cold water layout have to be considered in the earlier design stage to form an integrated system. The architect has to work along with the Civil Engineer, Structural Engineer and Building Services Engineer in the detail design as indicated in row nos. 6 to 59 of the matrix in Diagram 4. Different disciplines must work together efficiently and effectively in early architectural design stage providing clear and accurate information for the setting up of precast moulds in factory. Any rework can result in significant financial loss and wastage.

CONCLUSION

Prefabricating building elements off-site in precast design can effectively reduce generating construction waste on site. Standardization in design is a pre-requisite criterion for precast design and is most suitable for the design of high-rise residential buildings. Techniques that adopt information modeling such as ADePT have been proven to enable designers to visualize the complicated building design process and to increase efficiency by optimization. Feedback from designers at the start of the project revealed that they realize precast technique can reduce construction waste on site and the technique is becoming more popular. The research undertaken shows that the ADePT generic detailed design model may be adapted to model precast design in high-rise residential buildings. It is anticipated that the project will result in changes in philosophies and provision of new method for designers which can create a fundamental change within waste management.

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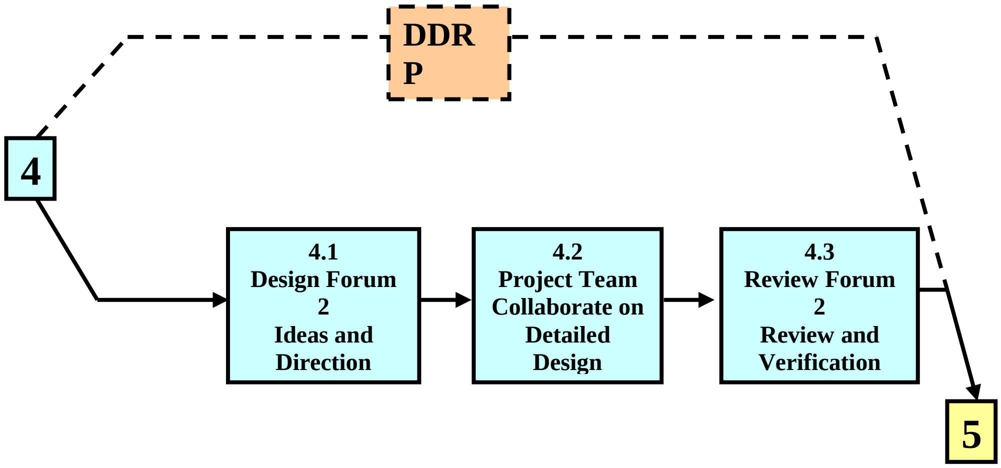

Figure 1 Master Flowchart –Work Stage 4 : Detailed Design and Specification

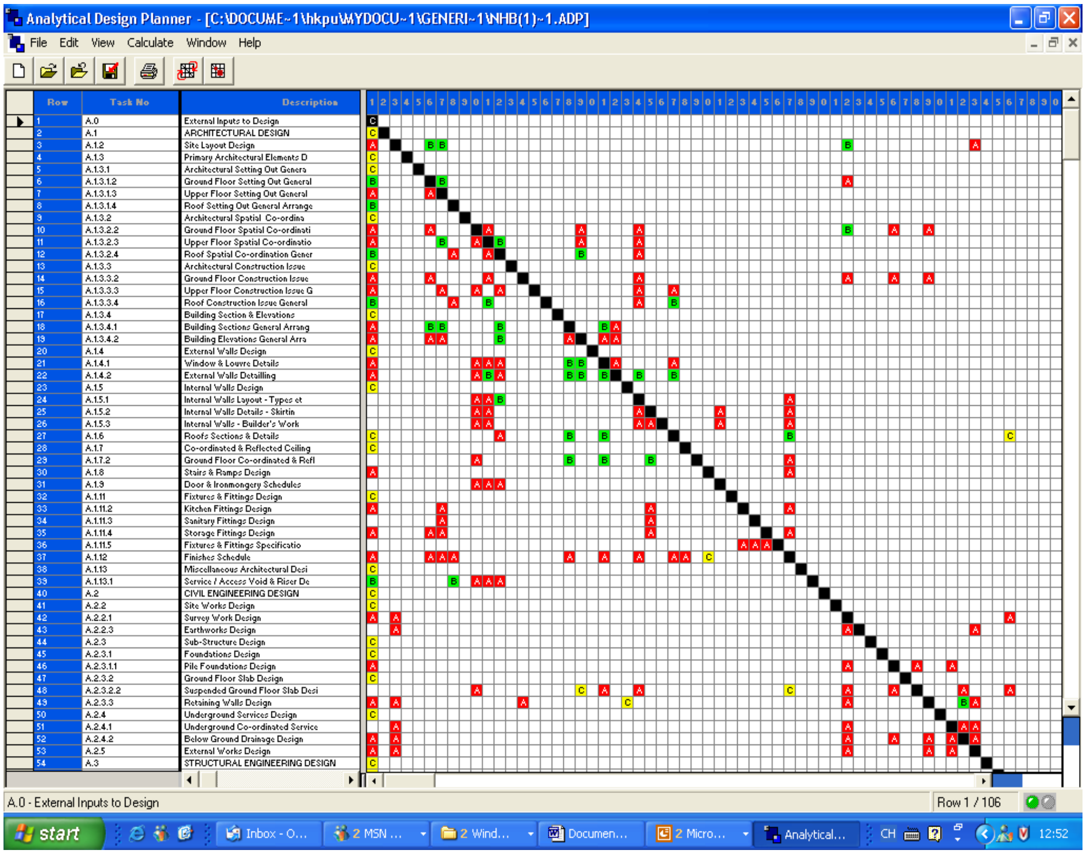

Diagram 1 NHB (1)

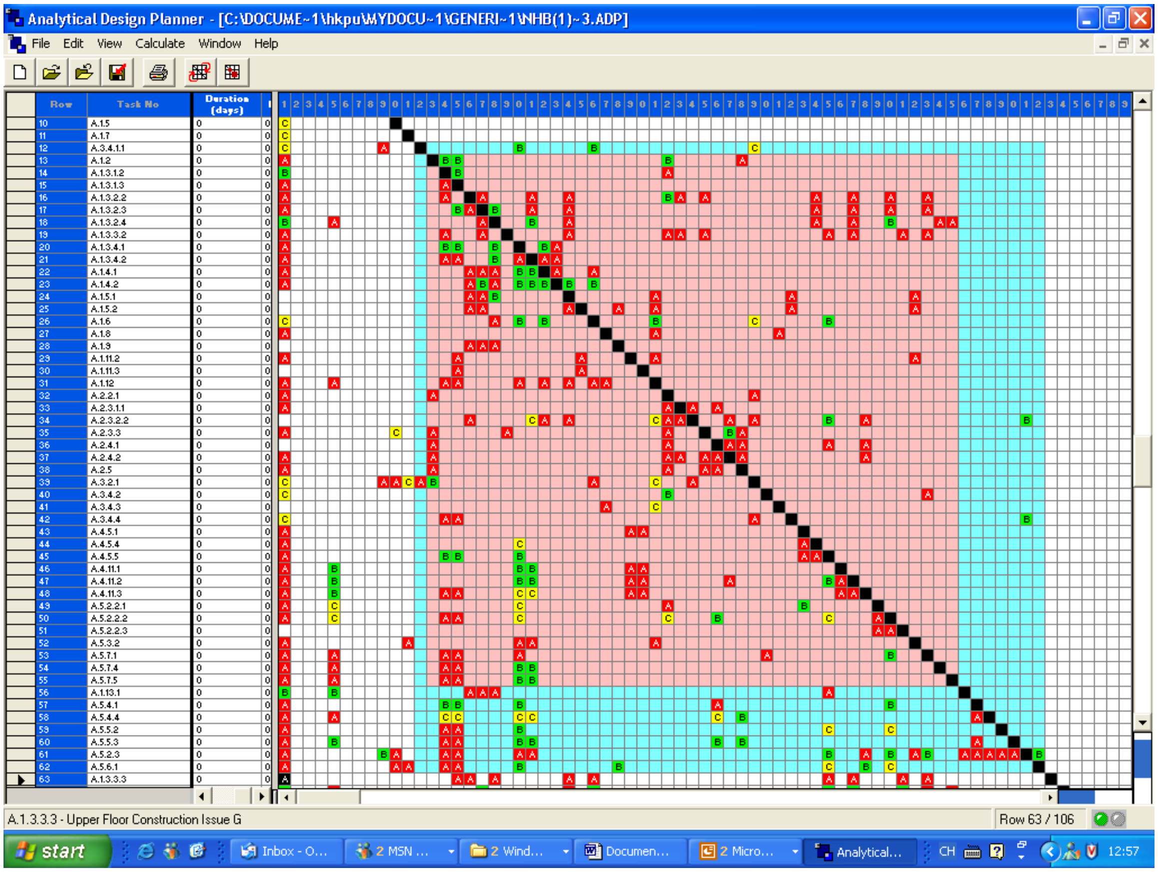

Diagram 2 NHB (1)_OPT

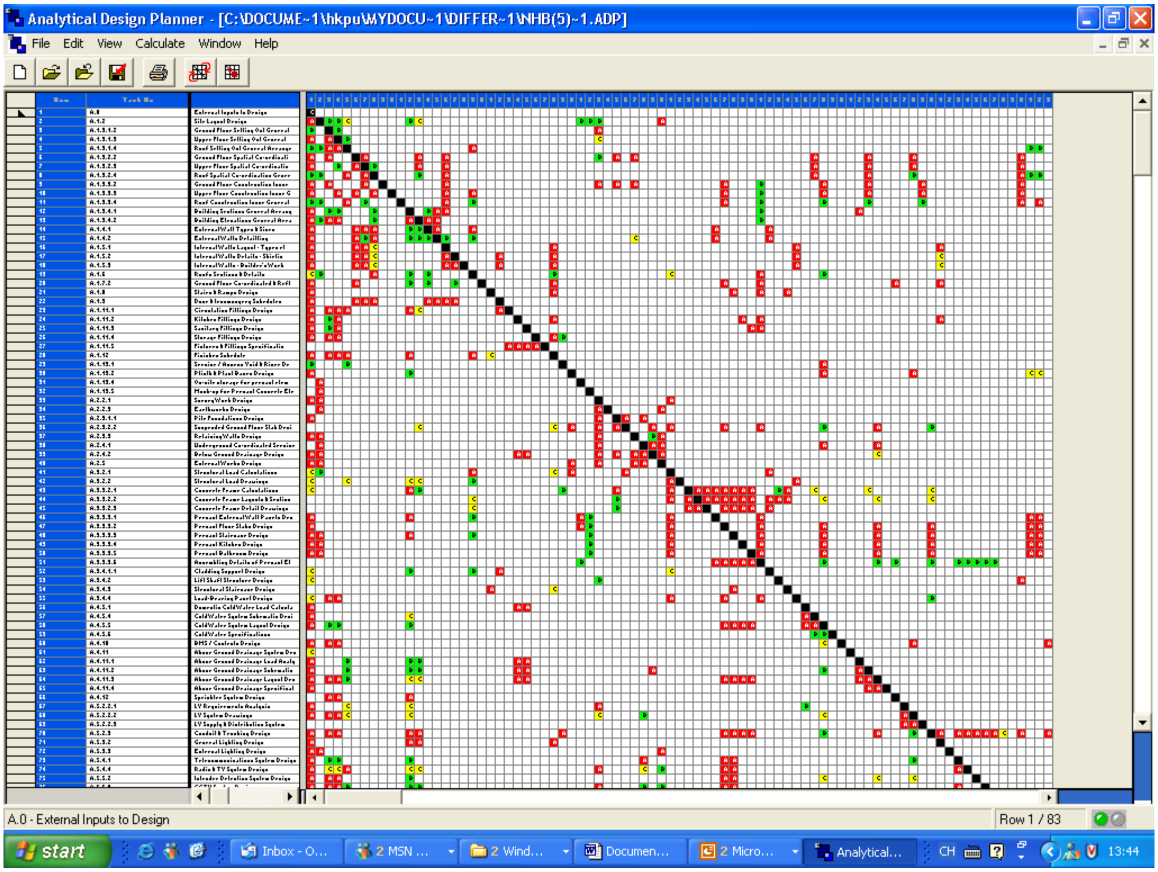

Diagram 3 NHB (5)

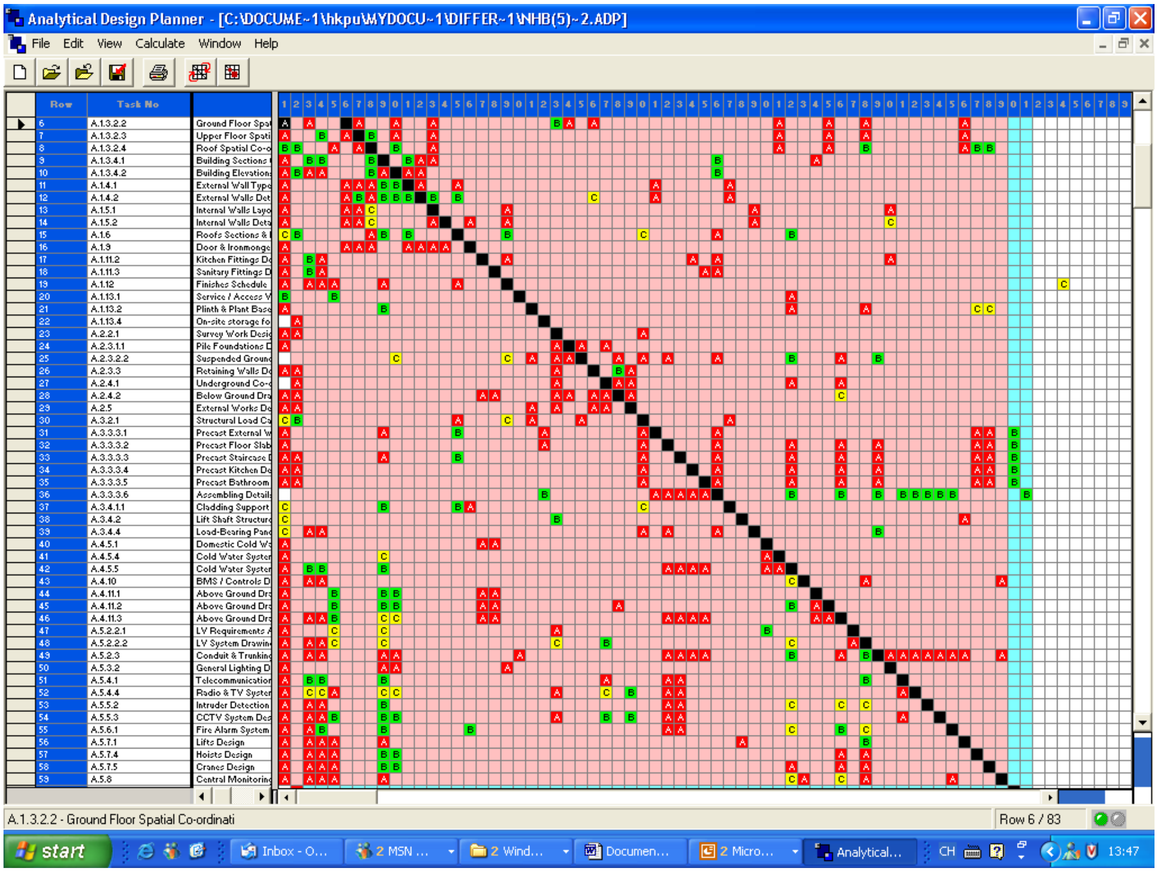

Diagram 4 NHB (5)_OPT