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The Use of a Multi-Criteria Decision Model to Choose Between Different Structural Forms Within Modern Office Construction

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The use of a multi-criteria decision model to choose between different structural forms within modern office construction

MPhil Thesis

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Dublin

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16, Holmview Avenue,
Omagh,
Co Tyrone,BT79 OAQ

Abstract

In 1993 the Steel Construction Institute carried out an economic analysis (including frame and overall construction time) of a number of structural options, for what is regarded as a typical office building, in outer Manchester. The study was later updated in 2004 due to changes in cost and new forms of construction notably the 'slimdeck' system. In 1994 the Steel Construction Institute carried out a study with regard to initial embodied energy on the same structural options considered in the 1993 publication.

This Project carries out a similar analysis of the 10 structural forms previously analysed by the Steel Construction Institute (SCI 1993, 1994 & 2004) in relation to cost, initial embodied energy, frame construction time and overall construction time. The research uses data gathered from the Irish construction industry. In Ireland the building is assumed to be on the outskirts of Dublin where site access is not a problem.

The study uses this information to rank the Irish options 1 to 10 on the basis of the four criteria. The ranking is achieved using various decision models. A similar ranking is carried out for the UK options.

The Project concludes with a comparison of the 2 sets of results and determines the preferred structural form in both Ireland and the UK.

1 Introduction to the project

The decision to use steel or concrete for the structural frame of a building is one of the most significant early decisions of any project. This choice has a wide-ranging effect on many subsequent aspects of the building design, programme and performance. These in turn will have an impact on the cost and value of the project and are fundamental to its overall success.

In 2004 the Steel Construction Institute produced a publication (SCI-P-137) 'Comparative Structure Cost of Modern Commercial Buildings'. The study compares the structure cost and time related costs of a number of regular forms of steel and concrete design used in modern multi-storey construction. The publication also examines the frame construction time and the overall construction time of each of the structural forms. The form of the building selected is representative and is chosen to draw out the important differences among the structural systems. A range of structural options is considered and comprise steel, composite and reinforced concrete alternatives. Inevitably, the regular forms of the buildings mean that they would be less complex and less costly in materials use than 'real' buildings of irregular form. Nevertheless, the comparison among all the options is still valid within these limits.

The generic open plan commercial building adopted is a 48.0m long and 13.5m wide rectangular four storey building. The total floor area of the building is 2,592m^2. An additional roof structure comprising roof portals, purlins and tiles is provided. It is clad in traditional brick outer leaf and inner leaf hollow block work, with regularly spaced individual windows making up a quarter of the building façade. The floor to ceiling height is 2.7m and there is a raised floor of 150mm in depth. A typical floor layout and cross-section are shown in Figures 1.1. and 1.2. An elevation is presented in Figure 1.3.

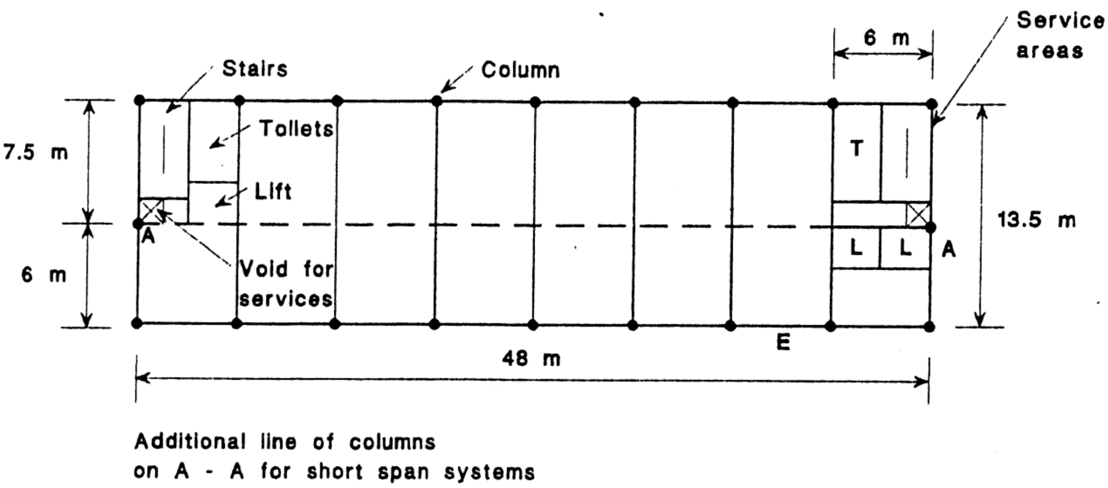

Figure 1.1: Typical floor layout (SCI 2004)

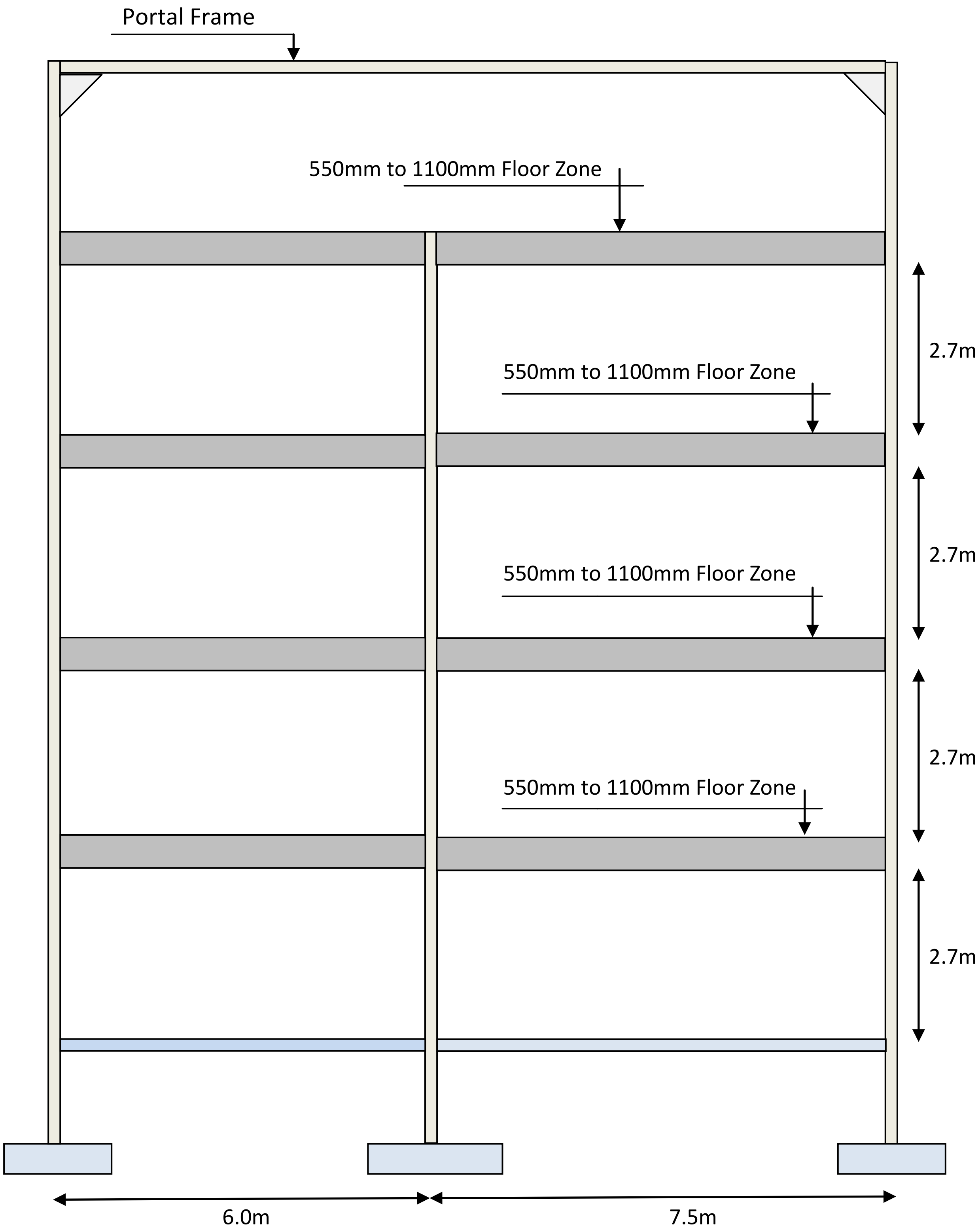

Figure 1.2 Typical Cross-section

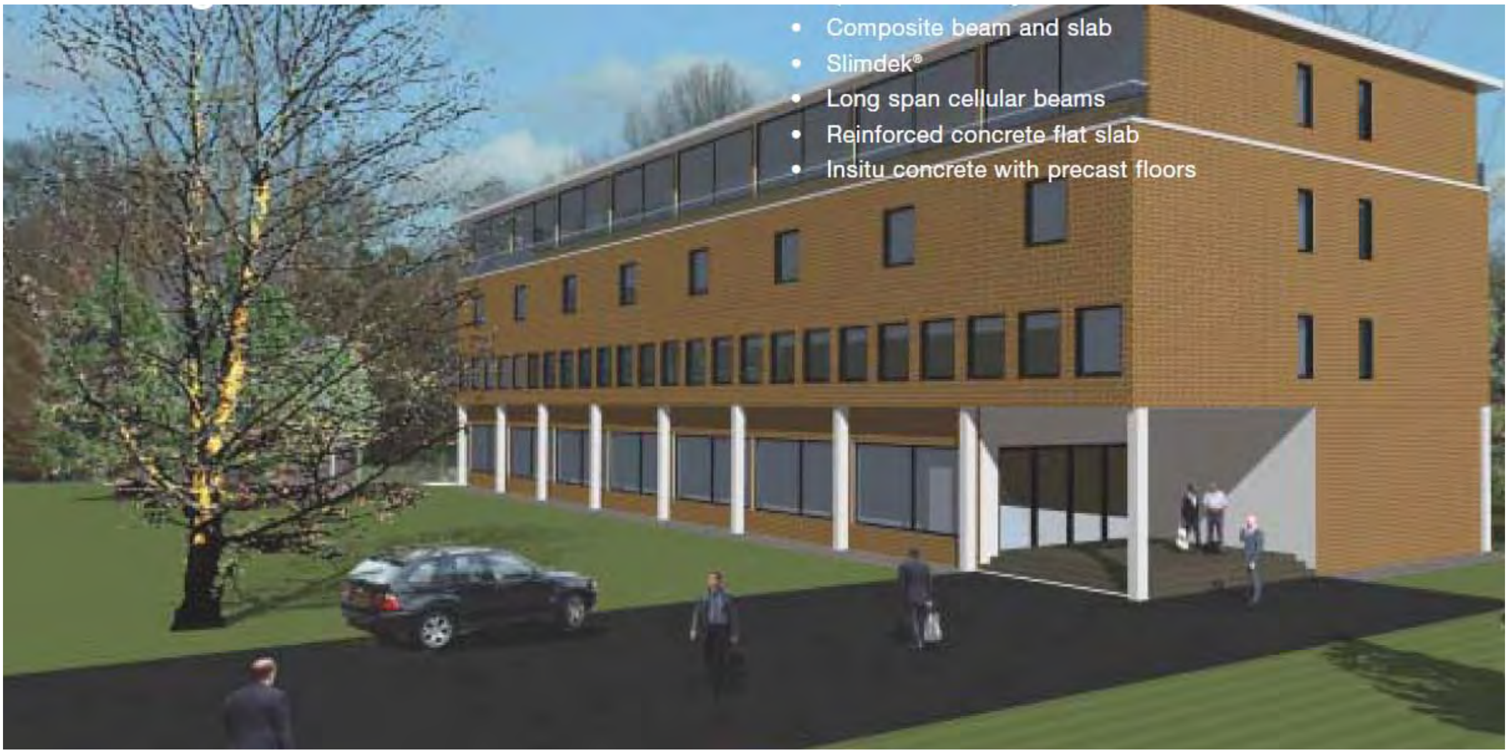

Figure 1.3 Building Elevation

The building is assumed to be located in outer Manchester in an area of major growth in steel construction and is typical of a speculative office building of modest specification. It is a four storey building, of a width that permits good natural ventilation and lets in plenty of natural light. The building is not air conditioned, but does have perimeter heating.

The structure is serviced from zones at each end of the building, where the stairs and lifts are also located. There are three 10-person lifts. Inside the building is generally open plan, but may be divided into individual offices and meeting rooms. It has a fire resistance of 60 minutes and is not sprinkler protected. The Approved Document B of the UK Building Regulations 1991 details the requirements for the provision of structural fire resistance in buildings. It states that the stability criterion is satisfied if "the load bearing elements of the structure of the building are capable of withstanding the effects of fire for an appropriate period without loss of stability". The Document recommends that a commercial building of five storeys or less has a fire resistance of 60 minutes if not sprinkler protected.

The foundations for this building are pad footings on sand, and the ground floor is not suspended. The top floor is designed to take the same loads as all other floors. Minor pipe work in this building is passed underneath or through the beams or floor. Provision for lighting units, fire protection, ceiling depths and an allowance for deflection are included in the depth of the floor zone.

The design of the steel/composite options was carried out by The Steel Construction Institute, 1994, using software and design tables according to BS 5950: Parts 1 & 3. They are designed as braced against wind load with bracing accommodated within the core area. Fire protection is taken as being board for columns and beams and spray for bracing members. Simflor® beams are partially concrete encased and only require board protection of exposed areas for 60 minutes fire resistance.

The design of the concrete options and the foundations for all designs was carried out by Ove Arup and Partners. They are braced against wind loading by reinforced concrete shear walls or cores. These designs follow BS 8110 for conventional reinforced concrete. Manufacturers' data was also used for the precast concrete designs.

Steel and concrete options were designed for a normal office floor loading of 3.5kN/m^2 plus 1.0kN/m^2 for partitions (BS 6399-1:1996 Part 1, Code of Practice Dead and Imposed Loads) and a roof load of 0.6kN/m^2 (BS 6399-3:1998 Part 1, Code of Practice for Imposed Roof Loads). The construction programming information for the building was provided by MACE Limited, UK. It is assumed that the programming and plant resources for all options are consistent so that they do not favour any form of construction. The building is erected using one mobile crane. A concrete pump is employed to install in-situ concrete and all concrete options use table forms. The steel columns are a maximum of two storeys high during construction and all options use pre-cast stairs.

The building cost data was provided for the Manchester building by Davis Langdon and Everest,UK. The information was obtained from a range of sources and concentrates on actual prices obtained in the last quarter of 2003.

In addition, while engineering building design focuses on optimising operational energy use, it tends to ignore the energy required to procure and construct a building. This energy, termed 'initial embodied energy', is directly related to the "mass" of a material and can be very significant when compared to operational energy. In 1994 the Steel Construction

Institute produced a publication 'A Comparative Environmental Life Cycle Assessment of Modern Office Buildings' which compares the initial embodied energy of the same structural forms analysed for cost, frame construction time and overall construction time in the SCI publication (2004). It was initiated by British Steel and the Department of the Environment, Transport and the Regions in 1994. The study focuses on initial embodied energy and embodied CO_2 emission values.

Its initial research revealed that several commercial material databases were in existence, incorporating embodied energy information. In the UK, much of this data relating to construction materials and products had been built up within large quantity surveying practices. This is because the method of breaking down buildings into components and quantities of materials (and thus mass), which is one of the standard techniques of quantity surveying, is the same as the additive calculation process necessary to determine the initial embodied energy of whole construction elements (floors, walls, stairs) and buildings.

The most comprehensive database for construction materials was available at Davis Langdon Consultancy. An embodied energy model was created for each construction alternative and for the transportation of materials and construction of the building. The material embodied energy (*mee*) values for construction were multiplied by the mass of each of the materials and in the same way initial embodied energy values were applied to the transportation and construction of the various elements. The results are set out in the SCI publication (1994).

For the purpose of this thesis, a similar study is carried out for the same generic building, assumed located on the outskirts of Dublin where access is not a problem, and based on the criteria of cost, initial embodied energy, frame construction time and overall construction time. It takes a number of the regular forms of steel and concrete construction analysed in the SCI publication (2004). The analysis considers only the variable structural elements i.e. foundations, concrete or steel frame and associated items, floors, stairs and cladding.

As part of the research work, four decision models were examined in order to identify the system most suited to the analysis of the multi-criteria information associated with the assessment of the different available structural options.

The models examined by the author were:

- Concordance Analysis (Roy, B. (1968))
- Goad Achievement Matrix (GAM) (Hill, M. (1968))
- Multi-attribute utility theory (MAUT) (Keeney, R. And Raiffa, H. (1976)
- Analytic Hierarchy Process (AHP) (Saaty, T.L. (1977)

Concordance Analysis is a multi-criteria decision model which uses various mathematical functions to indicate the degree of dominance of a given project option over the remaining ones. It operates by initially ascribing weights to the various criteria. Comparison between options proceeds on a pair-wise basis with respect to each criterion. These comparisons, combined with the weighting information, permit a ranking of all options to be generated.

The technique is readily applicable to the problems such as choosing the most appropriate structural form of a building, where data tends to be expressed in a variety of measurement scales, both monetary and non-monetary.

GAM evaluates each project option on the basis of how well each achieves a set of predetermined objectives. Because of its evolution from cost-benefit analysis, the estimation of costs and benefits is central to this method. Where the goal is defined in quantitative terms, costs and benefits will be expressed in their respective units. Where the goal is detailed in qualitative terms, benefits are expressed in terms of a perceived movement towards satisfying a qualitatively expressed objective, with costs expressed as a movement away.

The evaluation is presented in matrix form. A summation of final scores is only possible where all cost and benefits are expressed in the same units. Where this is not the case and data is mixed, a final GAM score is not obtained. In such cases, the final matrix can still be utilised as a method for presenting all information relevant to the decision process.

MAUT involves devising a function U which will express the utility of a project option in terms of a number of relevant decision criteria. The resulting performance of a given option will be based on the extent to which it maximises the value of the function U. Initially, the measurability of each decision criterion is established. Using this information, a utility function is devised for each, placing all measurements on a scale of 0 to 1 depending on the desirability / undesirability of each particular valuation of that criterion. Once scaling values which reflect the relative importance of each criterion are established to combine the utility functions of all relevant criteria and derive a final utility score for each option under consideration.

AHP reduces a decision problem to a series of smaller constituent parts. The relative merit of each project option is determined from a pair-wise analysis of the preference ratings for all combinations of project options, for each decision criterion involved. The relative importance of each criterion is also determined from a similar pair-wise analysis. The result of the overall process is a ranking of all options on an interval scale from 0 to 1, enabling the preferred option to be identified. AHP uses the eigenvector method both to determine the relative importance of the decision criteria and to determine a relative performance of the options on each of the chosen decision criteria. These are then combined in order to derive a resultant eigenvector which, when normalised, will give an overall ranking on a scale from 0 to 1 of all project options.

The above four techniques have the capacity to assess criteria measured in both monetary and non-monetary, quantitative and qualitative form. However, GAM retains the very narrowly based structure of cost-benefit analysis which will allow only a limited range of money-based criteria to be fully assessed, with other non-money based criteria evaluated in a less deterministic manner. MAUT provides a mathematically rigorous method of evaluation, but where data is of variable quality, the mathematical rigour of the method may obscure the uncertainties in the final result. Also, the 'trading-off' process which is central to MAUT could be seen as misplaced given the diverse range of criteria utilised within the author's analysis. AHP possesses a simplicity which MAUT lacks, however, its use of a relatively blunt 9-point semantic scale is seen as limiting its ability to distinguish between the performance of criteria which are measured in different units / scales.

Concordance analysis is a rigorous yet adaptable technique which allows the evaluation of mixed data, both monetary and non-monetary. It does not rely on the direct trading off of diverse engineering criteria and does not derive a strict ranking of all options where the quality of data is not sufficiently high to deliver this information. Views of different stakeholder groups can be readily taken into account within the method using their assigned criterion weightings.

Therefore, on the basis of this analysis, Concordance Analysis is identified as the decision-model suited to choosing between competing complex structural engineering options. A Concordance technique known as the Promethee1 Model (Brans, J.P. and Vincke, P. (1985)) is utilised within this model.

In addition, two very basic decision models (Borda Sum of Ranks and the Dominance Method) are used within this thesis in order to initially identify the better performing structural forms within the analysis. The more detailed analysis of options providing a detailed performance ranking is derived using the Promethee 1 Model.

The project analyses the results from Dublin and Manchester separately and produces a scoring/ranking of options in each case and decides on the favoured structural option in each location.

2 Aims, Objectives and Methodology of the Research

2.1 Aims

The aim of the study is to use a multi-criteria decision analysis (MCDA) model where different representative structural forms within office block construction are assessed on the basis of economic, environmental and technical criteria. The criteria are measured for a number of different structural options and a multi-criteria model produced based on results from Dublin and Manchester to assess information, produce a scoring/ranking of options and thus provide a preferred solution for each location.

The generic building in Dublin is assumed to be of identical layout, construction and specification to the structure studied in Manchester (SCI 1994 & 2004). A selection of the structural forms analysed in the SCI publications is assessed for the building in Dublin.

2.2 Objectives

The objectives of the project can be listed as follows;

- Compare a wide range of viable construction options.
- Identify criteria relevant to the decision making process for selecting the optimum structural form.
- Construct an innovative decision model which will enable a suitable structural form for office block construction be identified and assessed.
- Assess the appropriateness of MCDA for providing a methodology within which the optimum structural form for office block construction can be identified.

2.3 Methodology

- Assemble a number of structural forms and decision criteria
- Determine how each criterion is to be measured
- Collect the relevant information on the different structural forms considered and their scoring on the criteria proposed.
- Survey stakeholders/decision makers (client, planning authority, contractor, design team) to assess the relevant importance of the decision criteria.
- Select a number of decision models and apply the data to them
- Select the most appropriate decision model and decide on the optimum structural form.

The ten structural forms which are chosen for the purpose of economic, environmental and technical analysis, are based on the SCI Publication (2004) 'Comparative Structure Cost of Modern Commercial Buildings'. They include virtually every regular form of steel and concrete design used in modern multi-storey construction'. However, for the purpose of this thesis, which is to select an optimum solution based on a number of criteria, only the ten most cost-effective options for each material type are selected.

The 10 structural systems considered for the study are itemised below:

1. Slimflor℗ beams and pre-cast hollow core floor slab
2. Slimflor℗ beams and deep deck floor (un-propped)
3. Slimflor℗ beams and deep deck floor (propped)
4. Composite beams and composite slabs
5. Cellular beams or castellated beams and composite slabs
6. Composite beams with web openings
7. Reinforced concrete flat slab
8. Pre-cast hollow core units on reinforced concrete edge beams
9. Reinforced concrete waffle slab
10. Pre-cast double T units on reinforced concrete edge beams

The four criteria which are considered to be of importance in the selection of the optimum structural form are:

1. Cost
2. Initial embodied energy
3. Frame construction time
4. Overall construction time

The assessment of the ten structural options is carried out in relation to the structure only and does not include the roof, mechanical and electrical works, windows and doors, internal walls and partitions, floor and ceiling finishes, sanitary and general fittings. These items do not vary from one structural form to another and are therefore not relevant to this research. The ground floor is a reinforced concrete slab on hardcore fill. While there is no variation in the basic cost of the ground floor across all structural forms the concrete frame options begin 2 weeks later than the steel forms due to the need to construct the ground bearing slab first. This will have an effect on the preliminaries and thus increase the overall cost of the concrete options. Preliminaries are discussed later in chapter 4. The slab is used as a platform for propping the formwork to the concrete upper floors. The variable items for costing purposes are foundations, concrete or steel frame and associated items, floors, stairs and cladding. The reinforced concrete ground floor slab is the only non-variable element assessed.

The structure in Dublin is assumed to be of identical layout, construction and specification to the structure researched for Manchester. The design of the concrete, steel and composite options are taken directly from the SCI publication (2004) and are in accordance with BS 5950: Parts 1 & 3 for steel and composite design and BS 8110 for conventional reinforced concrete design. A fire resistance of 60 minutes is applied in accordance with the Irish Building Regulations 1997. These designs are used to cost the various elements within the ten structural forms for Dublin.

The unit cost rates obtained for the building in Dublin reflect 2008 competitive pricing. The unit rates, frame construction and overall construction times are provided by the Surveying department of Cormac Construction, Dublin.

The initial embodied energies for the steel and concrete options considered are based on the energy used in material production, transportation and in their eventual construction on site. The initial embodied energy values for material production in Ireland are obtained from The Inventory of Carbon & Energy (ICE) 2006. These values differ from those used in the SCI publication, 1994, which analysed the initial embodied energy for production in Manchester. The publication used information from the comprehensive database for construction materials available at Davis Langdon Consultancy, at that time, and generated embodied energy (*mee*) coefficients for production of various building materials. Initial embodied energy intensities depend on the location of a building as the distance from site to the source of the material can vary, as can the way in which materials are made. The purpose of this study is to determine if the scoring of initial embodied energy for each of the structural options is the same for Dublin and Manchester and then to use a multi criteria analysis model to rank the structural forms in both locations.

Data for sea and road transport is sourced from the Building Research Establishment – UK, 1999, as energy intensity of sea and road transport is similar in both the United Kingdom and in Ireland.

Statistical data on construction from the Department of Trade and Industry, UK is combined with energy production data obtained from Sustainable Energy Ireland to calculate the embodied energy due to construction. Energy use in the construction process is sourced from the UK because of the similarity in the construction industry in the two countries and the lack of equivalent Irish data.

The research is divided into three main categories:

1. Comparison of the various options within the Irish construction industry in relation to the following parameters:

- Cost
- Initial embodied energy
- Frame construction time
- Overall construction time

2. Comparison of the various options between the Irish and British construction industries in relation to cost and initial embodied energy. Obtain from the SCI publication, 2004, the frame construction time and overall construction time in Manchester for use in the multi-criteria decision model.

3. The use of a multi-criteria decision analysis model to assess information from 1 and 2 above and produce a scoring/ranking of options for both Dublin and Manchester.

3 Structural options

3.1 Introduction

The structural drawings of one quarter of the building plan are presented in Figures 3.1.1 to 3.1.6 for the steel and composite options and Figures 3.1.7 to 3.1.10 for the concrete options.

One of the main requirements of the building is that the clear height between finished floor level and underside of ceiling is kept to a minimum of 2.7m. The height of the vertical elements, such as columns, stairs and masonry cladding, is not the same for each structural option. This is a function of the depth of the floor structure which is added onto the clear height of 2.7m and varies depending on the type of structural form used. For example, the slimfor® beams and pre-cast hollowcore slab require a structural depth of 565mm while the cellular beams and composite slab require a structural depth of 1,075mm. The difference in height per storey is 510mm and over four storeys this amounts to 2,040mm. This clearly adds to the volume of the vertical members of the cellular beams and composite slab structural form. Table 3.1.1 summarises the depth of floor required for each option.

The 10 structural options are as follows:

- Slimflor® beams and pre-cast hollow core floor slab
- Slimflor® beams and deep deck floor (un-propped)
- Slimflor® beams and deep deck floor (propped)
- Composite beams and composite slabs
- Cellular beams or castellated beams and composite slabs
- Composite beams with web openings
- Reinforced concrete flat slab
- Pre-cast hollow core units on reinforced concrete edge beams
- Reinforced concrete waffle slab
- Pre-cast double T units on reinforced concrete edge beams

Table 3.1.1: Depth of floor zone (mm)

STRUCTURAL OPTION	Raised Floor	Floor Slab	Deck	Beam	Ceiling	Total
Option 1 **Slimflor® beams and pre-cast hollowcore slab**	150.0	215.0	____	____	200.0	**565.0**
Option 2 **Slimflor® beams and deep deck floor(un-propped)**	150.0	80.0	225.0	____	200.0	**655.0**
Option 3 **Slimflor® beams and deep deck floor(propped 7.5m)**	150.0	70.0	225.0	____	200.0	**645.0**
Option 4 **Composite beams and floor slab**	150.0	120.0	____	313.0	200.0	**783.0**
Option 5 **Cellular beams or castillated beams and composite slab**	150.0	120.0	____	655.0	150.0	**1 075.0**
Option 6 **Composite beams with web Openings**	150.0	120.0	____	602.0	150.0	**1 022.0**
Option 7 **Reinforced concrete flat slab**	150.0	300.0	____	____	200.0	**650.0**
Option 8 **Pre-cast hollow core units on reinforced concrete edge beams**	150.0	75.0	400.0	____	200.0	**825.0**
Option 9 **Reinforced concrete waffle slab**	150.0	400.0	____	____	200.0	**750.0**
Option 10 **Pre-cast double T units on reinforced concrete edge beams**	150.0	75.0	500.0	____	200.0	**925.0**

A brief description of each of the structural options is given below:

3.2 Slimflor® beams with pre-cast concrete slab (Figure 3.1.1)

In this form of construction the pre-cast concrete slab and steel beams occupy the same depth so that the floor has a flat soffit. A steel plate is welded to the bottom flange of a UC section to provide the necessary support to the slab, and in-situ concrete is poured around the section. No fire protection is required for up to 60 minutes fire resistance because of the partial encasement of the section.

3.3 Slimdek® propped and un-propped (Figures 3.1.2 & 3.1.3)

Slimdek® is the collective term for the following methods of Slimflor® construction:

1. Slimflor® beam (SFB)
2. Asymmetric Slimflor® Beam (ASB)
3. RHS Slimflor® Edge Beam (RHSFB)
4. A deep profiled steel deck (SD210)

In many cases a long span floor cannot support the wet concrete floor during construction. Wet concrete has no strength and therefore no bending resistance. It does not act compositely with the floor deck. In order to avoid excessively deep floors and to reduce the depth of concrete floor over the steel deck, the floor may be propped during construction at some point along the span. The span of the floor is reduced and can now carry the wet concrete. Once the concrete has hardened the prop may be removed. The concrete can now act compositely with the floor i.e. the compression is resisted by the concrete and the tension by the steel beam. The prop should not be removed until the concrete has hardened and achieved its design strength.

The general benefits of using Slimdek® construction are:

1. Floors have a flat soffit which offers unhindered passage for the services.
2. The overall floor construction depth is reduced. This has an influence on the cladding costs i.e. the overall height of the building is reduced.
3. Slimflor® construction is similar to other 'fastrack' methods for speed of construction.
4. It improves the fire resistance of the section. The concrete that surrounds the beam partially insulates the section, giving in the order of 60 minutes fire resistance. This can therefore eliminate the need for additional fire protection.
5. The concrete that surrounds the beam produces an increase in the second moment of area of the section. This enhancement is helpful in reducing deflections.

3.4 Composite beam and slab (Figure 3.1.4)

Composite slabs comprise profiled steel decking as the permanent formwork to the underside of concrete slabs spanning between support beams. Spans of the order of 2.5m to 4.5m between support beams are common, and beams are usually designed to span between 6.0m and 12.0m. A shallow lightweight concrete slab is cast on the decking and composite action between the beam and slab is achieved by shear studs that have been welded through the decking on to the supporting beams. Composite action is responsible for a considerable increase in the load bearing capacity and stiffness of steel beams, which when utilised in design, can result in significant savings in steel weight and in construction depth. These economies have largely accounted for the dominance of composite steel frame construction in the commercial building sector in recent years.

This structural form is the industry standard and has approximately a 50% market share of the low rise frame construction for offices (Corus, Ireland).

3.5 Long span cellular or castellated beams (Figure 3.1.5)

Beams may be fabricated with regular openings by automatic cutting and re-welding of sections. In the castellated beam the openings are hexagonal and circular in the cellular beam. The openings are filled in close to the supports and at the location of point loads. Cellular and circular beams provide long clear spans offering tremendous flexibility of space. The use of composite cellular/castellated beams for long-span construction is now well established and recognised for its suitability at keeping floor zones to a minimum by passing the services through the circular openings. The effective span range is 10.0m to 18.0m. The beams are usually treated with an intumescent fire protective coating which is applied off-site.

3.6 Composite beams with web openings (Figure 3.1.6)

Large openings are formed in the webs of the composite beam for the passage of service ducts. As the web contributes more to the shear resistance than the bending resistance of the beam, the optimum location of the opening is in the low shear zone. Openings of up to 70% of the beam depth, with a length/depth ratio of up to 2 may be achieved.

3.7 Reinforced concrete flat slab (Figure 3.1.7)

A flat slab is a reinforced concrete slab supported directly by concrete columns without the use of intermediary beams. The slab may be of constant thickness throughout or in the area of the column it may be thickened as a drop panel. The slab is thicker than that required in T-beam floor slab construction but the omission of beams gives a smaller storey height for a given clear height which makes it more economical.

This structural form is a popular concrete option and, although more labour intensive, requires only traditional skills i.e. shuttering, steel fixing and pouring of concrete, to build.

By definition, it offers a flat soffit, which makes the incorporation of services easier. It is a heavier form of construction, but can be used successfully for floor spans of up to 7.5m. Windows can extend up to the underside of the slab, and there are no beams to obstruct the light and the circulation of air. The absence of sharp corners gives greater fire resistance as there is less danger of the concrete spalling and exposing the reinforcement.

3.8 In-situ concrete beams and columns with pre-cast hollow core slab (Figure 3.1.8)

Hollow core slabs are pre-cast, pre-stressed concrete elements that are generally used for flooring. Some of the advantages are:

- Long spans, no propping
- Flexible in design
- Fast construction
- Lightweight structures
- Floor voids and penetrations are available, and special trimmer beams.

The slabs are generally 1.2m in width and of varying spans. They have between four and six longitudinal cores running through them, the primary purpose of the cores being to decrease the weight, and material within the floor, yet maintain maximum strength. The slabs vary in depth from 150mm to 400mm depending on the span and applied loading. The slabs can be supported on inverted in-situ T-beams. This reduces the depth of the structural floor and thus the overall height of the building (section A-A)

This form of construction is common for low rise buildings and offers relatively long spans compared with a reinforced concrete slab.

3.9 Waffle Slab (Figure 3.1.9)

In this form of construction temporary void forms are provided in the soffit to create a waffle appearance. A 400mm deep slab is required for a 7.5m square grid and the slab depth over the thinnest part is 100mm, for fire resistance and local load requirements. The void formers are omitted near the columns to improve the shear transfer.

3.10 Pre-cast double T-beams (Figure 3.1.10)

Double T-beams are in the form of ribbed beams cast in pairs. The ribs are pre-stressed in order to improve their stiffness and resistance against cracking. While the depth of the T-beam is compatible with the composite options, a substantial edge beam is required to support the T-beams in order to offer shear resistance.

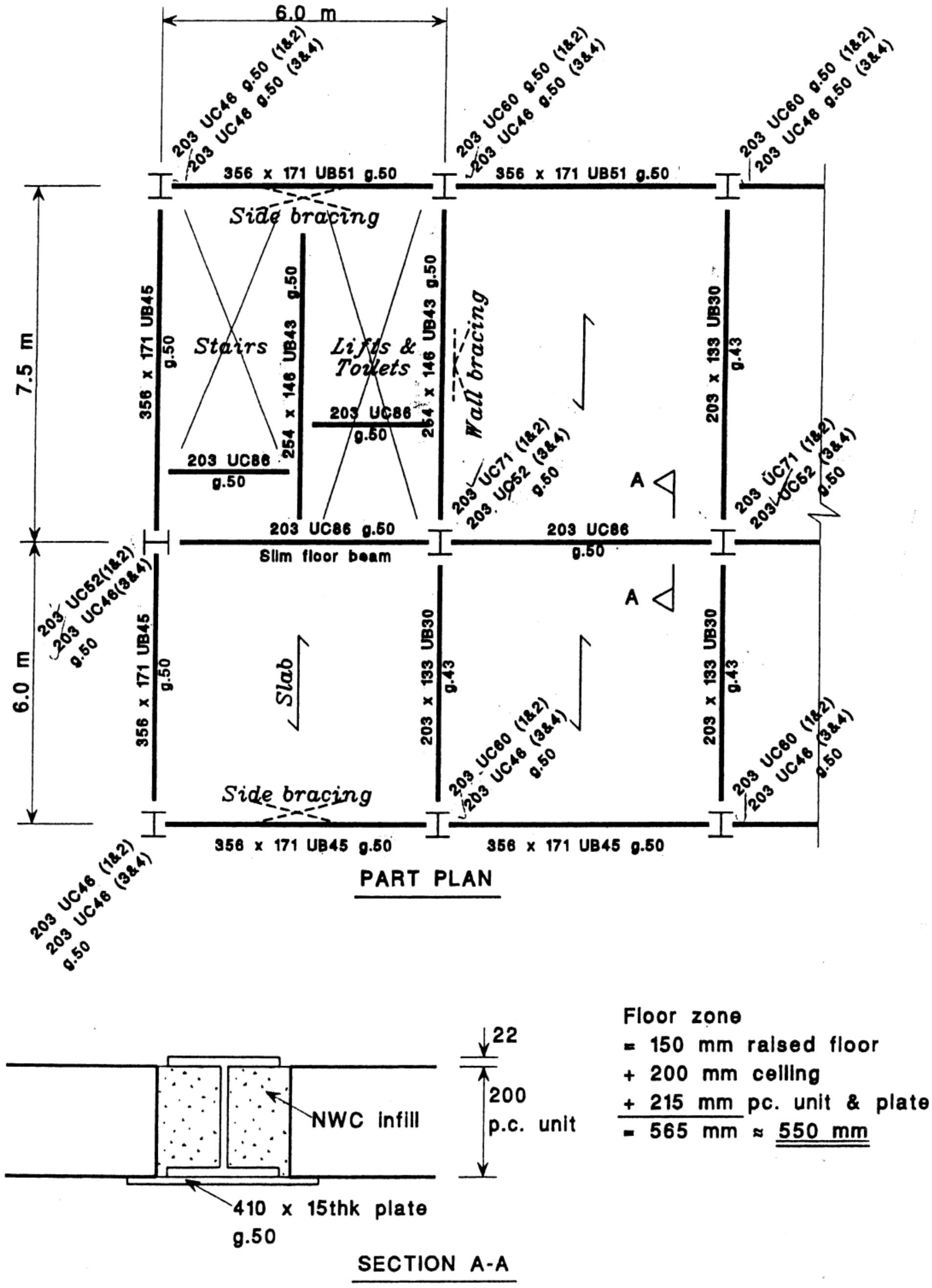

Figure 3.1.1 Slimflor® beams with pre-cast slab (SCI 2004)

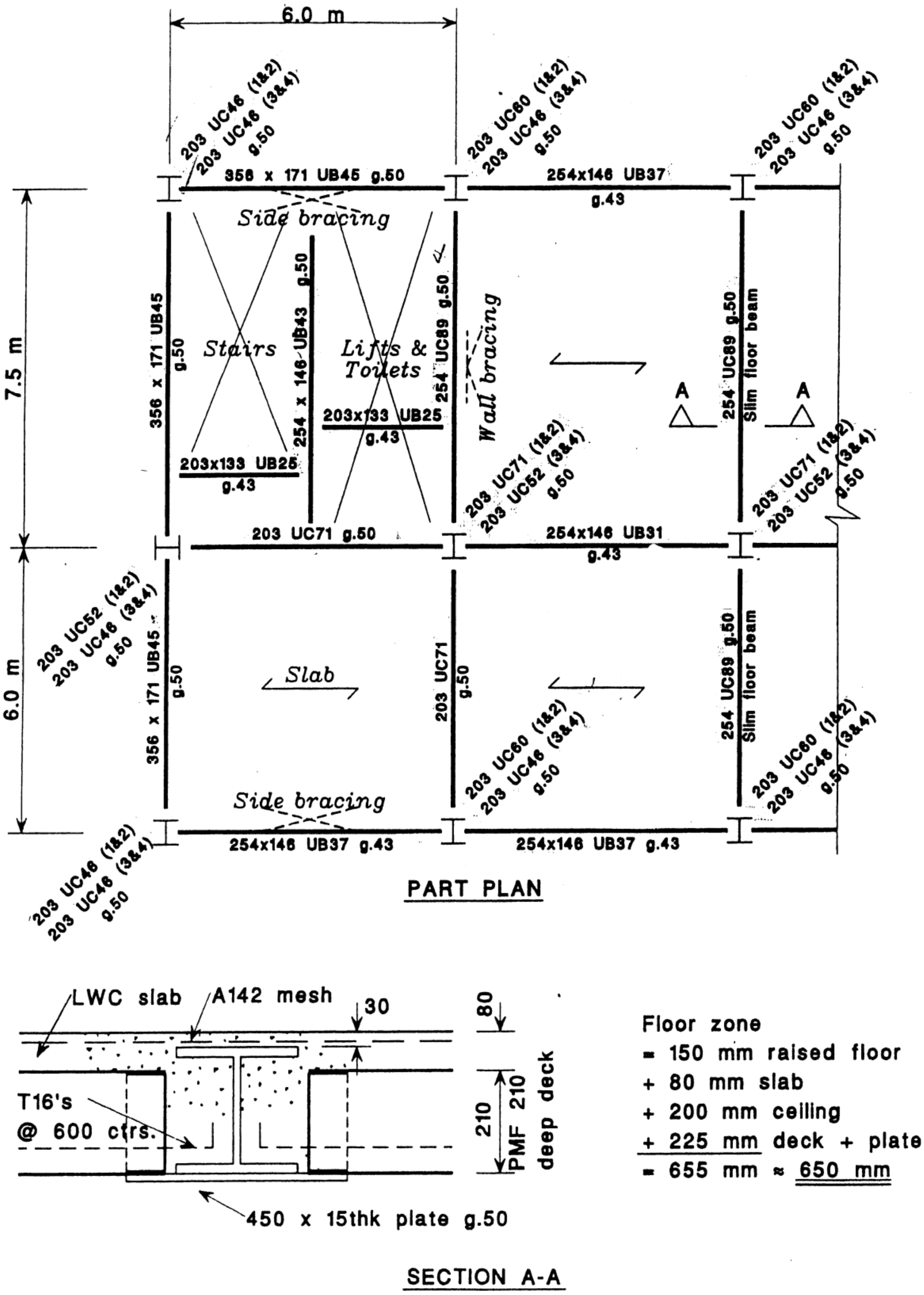

Figure 3.1.2 Slimflor® beams and deep deck floor (un-propped) (SCI 2004)

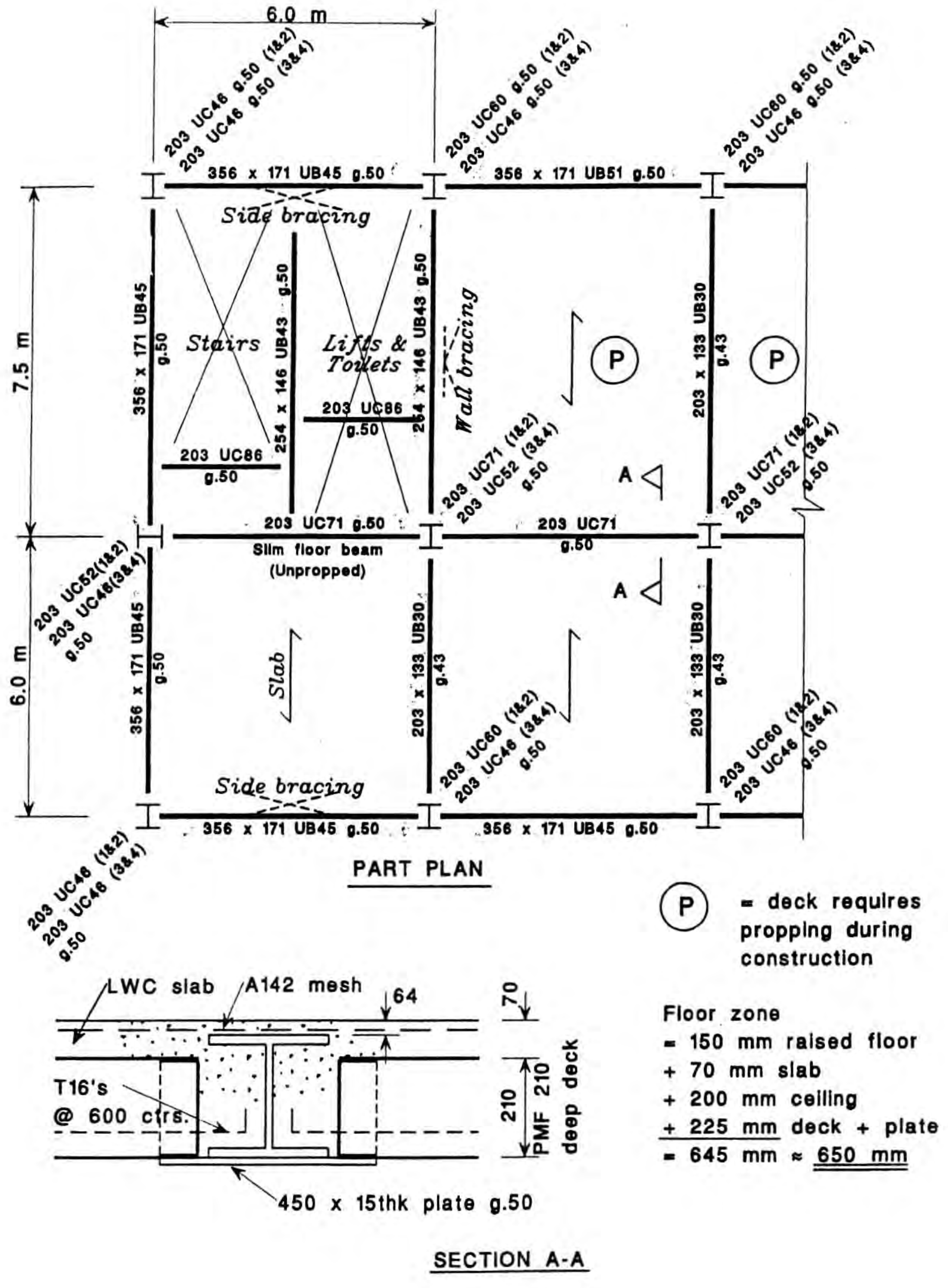

Figure 3.1.3 Slimflor® beams and deep deck floor (propped) (SCI 2004)

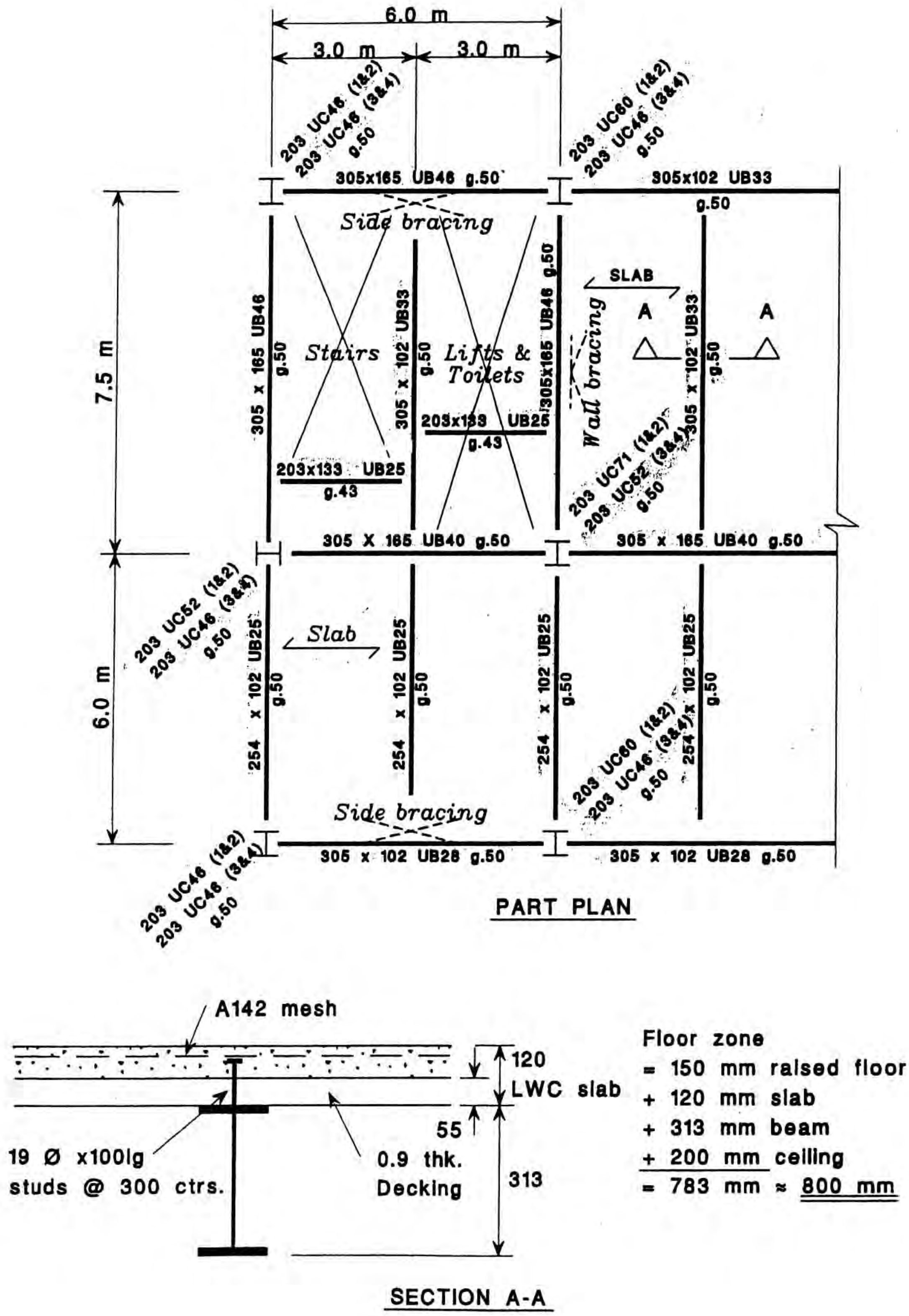

Figure 3.1.4 Composite beams and composite slabs (SCI 2004)

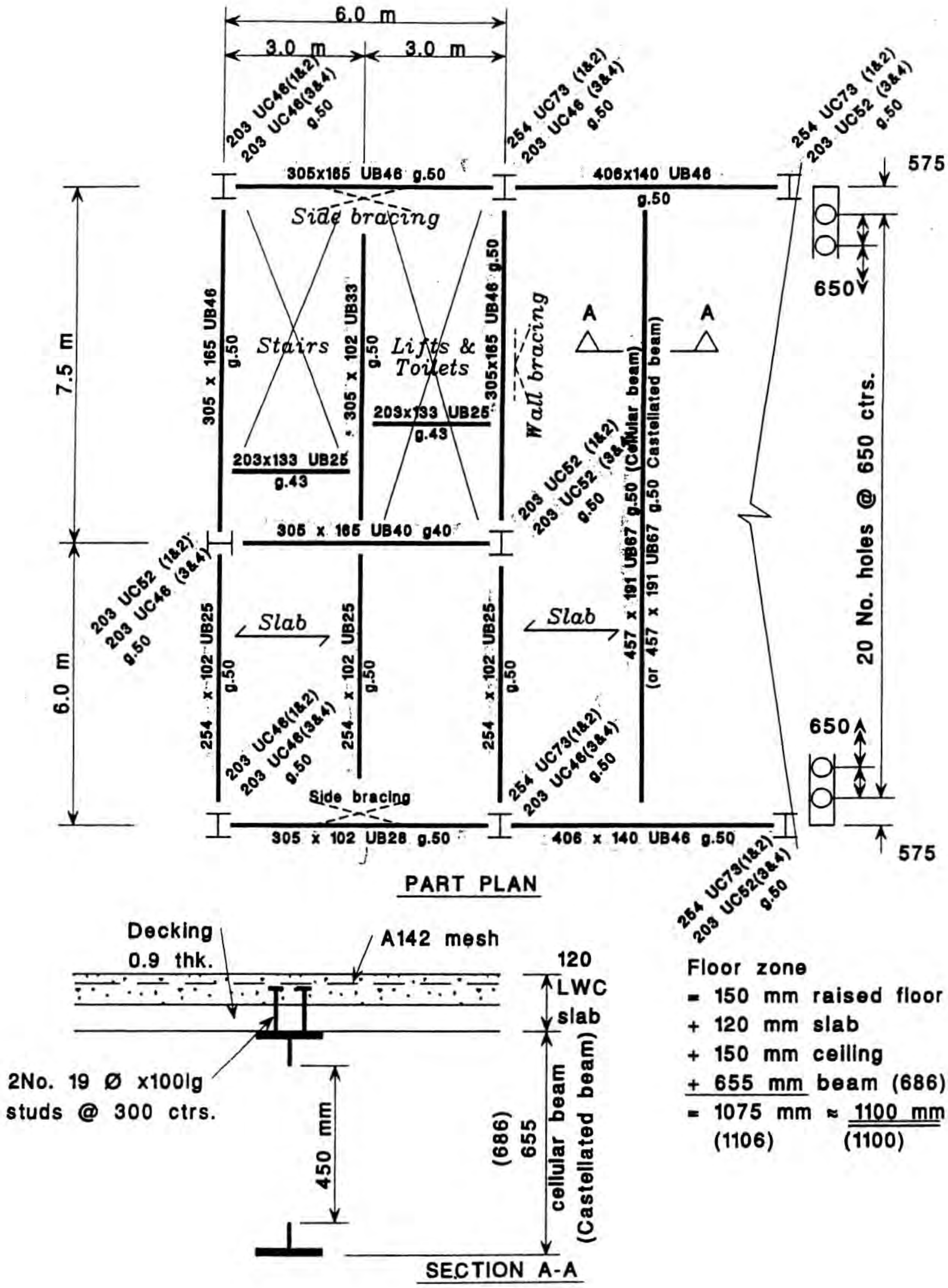

Figure 3.1.5 Cellular beams or castellated beams and composite slabs (SCI 2004)

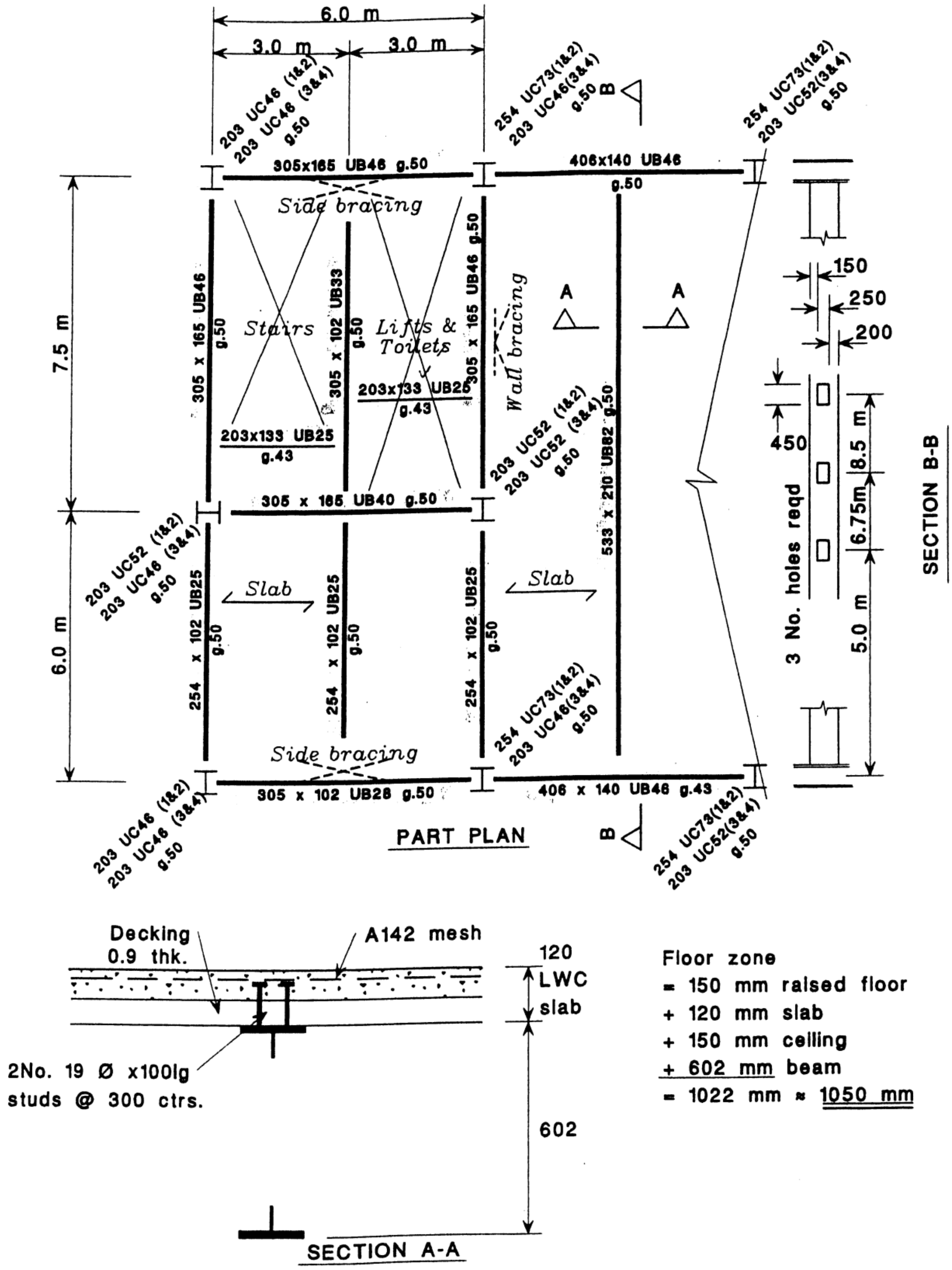

Figure 3.1.6 Composite beams with web openings (SCI 2004)

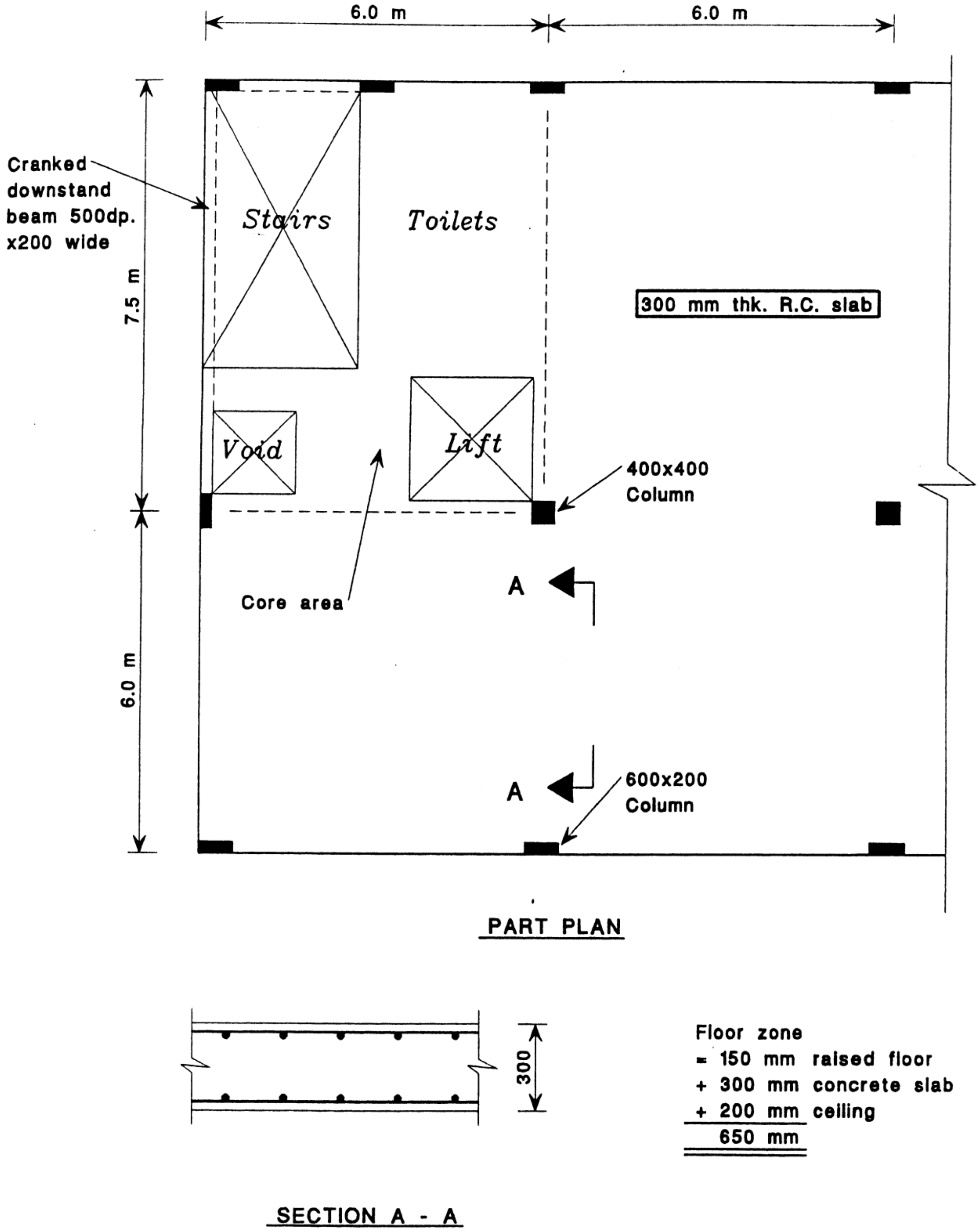

Figure 3.1.7 Reinforced concrete flat slab (SCI 2004)

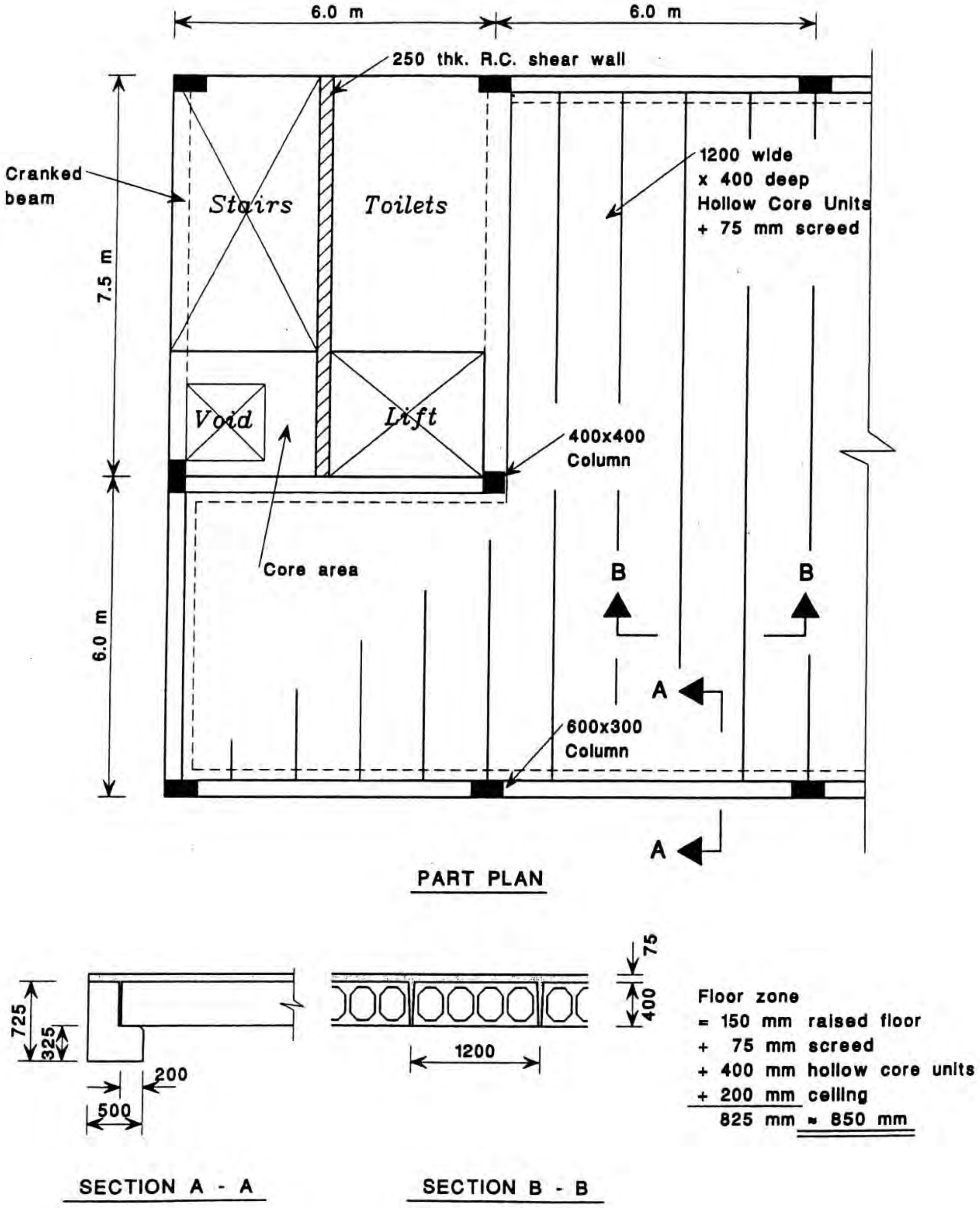

Figure 3.1.8 Pre-cast hollow core units on reinforced concrete edge beams (SCI 2004)

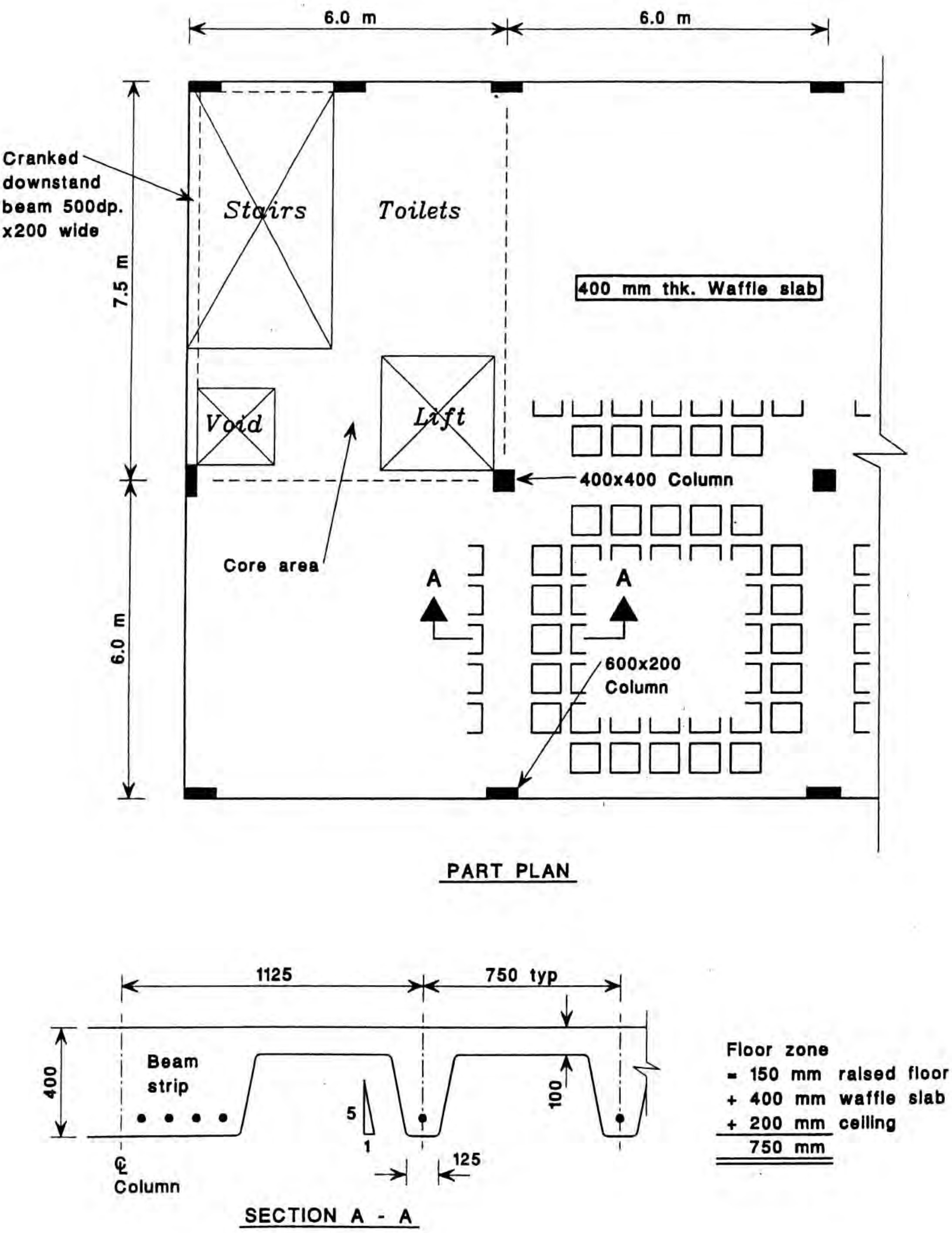

Figure 3.1.9 Reinforced concrete waffle slab(SCI 2004)

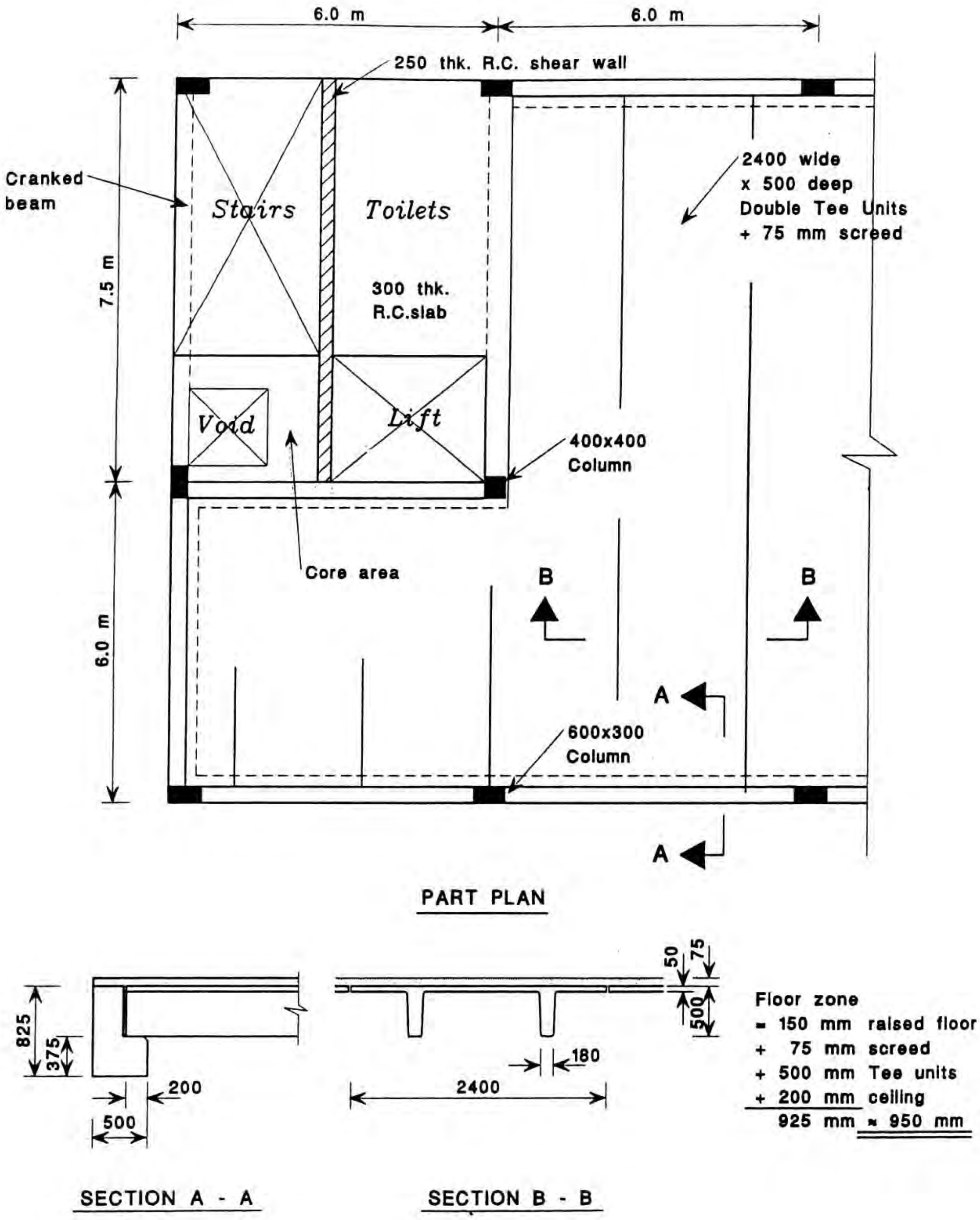

Figure 3.1.10 Pre-cast double T units on reinforced concrete edge beams (SCI 2004)

4 Comparison of the various options within the Irish construction industry

4.1 Cost

The comparative cost of the 10 structural options is carried out in relation to the structure only and does not include steel roof, mechanical and electrical works, windows and doors, internal walls and partitions, floor and ceiling finishes, sanitary and general fittings.

A Bill of Quantities, showing the element unit rates, is drawn up for each of the 10 structural solutions. This information is set out in detail in Tables 4.1.1 to 4.1.38.

The rates applied for the various steel options are obtained on the basis of recently tendered projects and include steel protection, paintwork, transportation and erection. The itemised rates for the various concrete components which include foundations, upper floors (pre-cast and in-situ), roof, columns and beams, and the associated work items of reinforcement and formwork are also derived from recently tendered projects. The rates for masonry are relevant to a 215mm hollow block inner leaf and a 100mm brick outer leaf. All stairs and landings are pre-cast and rates are supplied by McGrath Pre-cast Concrete, Co. Clare. The itemised rates are provided by Cormac Construction, Dublin.

As discussed in Chapter 3 the height of the vertical elements, such as columns, stairs and masonry cladding, is not the same for each structural option. This is a function of the depth of the floor structure which is added onto the clear height of 2.7m and varies depending on the type of structural form used. This has a significant effect on the cost particularly with regard to the number of columns and foundations required in a particular structural form. Some of the structural options have clear horizontal spans and therefore do not require internal columns. This has a greater effect on the concrete forms where labour intensive activities such as fixing of reinforcement, striking of formwork and installation of fire boarding can see the cost of the building escalate.

Table 4.1.1: Option 1 Slimflor® beams and Pre-cast hollow core floor slab

Item Description	Quantity	Unit	Euro/unit	Total
Steelwork				
356 x 171 UB 51 grade 50	2.45	T	2 300.0	**5 635.00**
254 x 146 UB 43 grade 50	5.16	T	2 300.0	**11 868.00**
203 x 133 UB 30 grade 43	9.54	T	2 300.0	**21 942.00**
356 x 171 UB 51 Slimflor® grade 50	12.00	T	2 300.0	**27 600.00**
356 x 171 UB 45 Slimflor® grade 50	19.72	T	2 300.0	**45 356.00**
203 UC 86 grade 50	6.19	T	2 300.0	**14 237.00**
203 UC 86 Slimflor® grade 50	25.15	T	2 300.0	**57 845.00**
100 x 100 x 12 angle grade 43	5.23	T	2 300.0	**12 029.00**
203 UC 71 grade 50	3.23	T	2 300.0	**7 429.00**
203 UC 60 grade 50	5.46	T	2 300.0	**12 558.00**
203 UC 52 grade 50	3.04	T	2 300.0	**6 992.00**
203 UC 46 grade 50	7.18	T	2 300.0	**16 514.00**
400 x 400 x 35 base plate 27 No.	1.2	T	2 300.0	**2 760.00**
M20 bolts 150mm long	108	no.	40.0	**4 320.00**
Connections-bolts, end plates, cleats, welds, etc.	10.44	T	2 300.0	**24 012.00**
Secondary steelwork	20.80	T	2 300.0	**47 840.00**

Sub Total 318 937.00

Table 4.1.2: Option 1 Slimflor® beams and Pre-cast hollow core floor slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.3 x 2.3 x 1.1 pad foundation Grade 40N20. 5 No.	29.0	m^3	135.0	**3 915.00**
Reinforcement to pad fnd. 35kg/m^3	1.0	T	1 200.0	**1 200.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 5 No.	7.5	m^3	115.0	**862.50**
2.0 x 2.0 x 1.0 pad foundation Grade 40N20. 20 No.	80.0	m^3	135.0	**10 800.00**
Reinforcement to pad fnd. 35kg/m^3	2.8	T	1 200.0	**3 360.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 20 No.	22.0	m^3	115.0	**2 530.00**
1.9 x 1.9 x 1.0 pad foundation Grade 40N20. 2 No.	7.22	m^3	135.0	**974.70**
Reinforcement to pad fnd. 35kg/m^3	0.253	T	1 200.0	**303.60**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 2 No.	2.0	m^3	115.0	**230.00**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
Concrete – Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**

Sub Total 71 378.75

Table 4.1.3: Option 1 Slimflor® beams and Pre-cast hollow core floor slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete - Upper Floors				
200mm deep hollow core units 4 No.floors	2 352	m^2	36.0	**84 672.00**
Normal weight concrete infill between beams and slab 35N20	40.0	m^3	125.0	**5 000.00**
Concrete – Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long.	8	no.	385.0	**3 080.00**
Precast concrete stairs 10/162.5mm risers 9/305mm treads	16	no.	4 000.0	**64 000.00**
Masonry				
215mm 5 N hollow block inner leaf	906.0	m^2	40.0	**36 240.00**
100mm 5N brick outer leaf	1 284	m^2	95.0	**121 980.0**
Fire Protection				
Board to steel columns 22mm thick	132.5	m^2	45.0	**5 962.50**
Board to soffit of steel beams 22 mm thick	215.0	m^2	45.0	**9 675.00**
Board to sides of steel beams within voids and lift shafts 22mm thick	70.0	m^2	45.0	**3 150.00**

Sub Total 333 759.50

Total 724 075.25

Table 4.1.4: Option 2 Slimflor® beams and deep deck floor (un-propped)

Item Description	Quantity	Unit	Euro/unit	Total
Steelwork				
254 x 146 UB 43 grade 50	2.58	T	2 300.0	**5 934.00**
254 x 146 UB 37 grade 43	12.43	T	2 300.0	**28 520.00**
254 x 146 UB 31 grade 43	4.47	T	2 300.0	**10 281.00**
203 x 133 UB 25 grade 43	1.80	T	2 300.0	**4 140.00**
356 x 171 UB 45 Slimflor® grade 50	8.58	T	2 300.0	**19 734.00**
254 UC 89 Slimflor® grade 50	46.20	T	2 300.0	**106 260.0**
203 UC 71 Slimflor® grade 50	11.45	T	2 300.0	**26 335.00**
100 x 100 x 12 angle grade 43	5.27	T	2 300.0	**12 121.00**
203 UC 71 grade 50	3.33	T	2 300.0	**7 659.00**
203 UC 60 grade 50	5.63	T	2 300.0	**12 949.00**
203 UC 52 grade 50	3.14	T	2 300.0	**7 222.00**
203 UC 46 grade 50	7.40	T	2 300.0	**17 020.00**
400 x 400 x 35 base plate 27 No.	1.2	T	2 300.0	**2 760.00**
M20 bolts 150mm long	108	no.	40.0	**4 320.00**
Connections - bolts, end plates, cleats, welds, etc.	11.23	T	2 300.0	**25 829.00**
Secondary steelwork	20.80	T	2 300.0	**47 840.00**
			Sub Total	**338 924.00**

Table 4.1.5: Option 2 Slimflor® beams and deep deck floor (un-propped)

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.3 x 2.3 x 1.1 pad foundation Grade 40N20. 5 No.	29.0	m^3	135.0	**3 915.00**
Reinforcement to pad fnd. 35kg/m^3	1.0	T	1 200.0	**1 200.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 5 No.	7.5	m^3	115.0	**862.50**
2.0 x 2.0 x 1.0 pad foundation Grade 40N20. 20 No.	80.0	m^3	135.0	**10 800.00**
Reinforcement to pad fnd. 35kg/m^3	2.80	T	1 200.0	**3 360.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 20 No.	22.0	m^3	115.0	**2 530.00**
1.9 x 1.9 x 1.0 pad foundation Grade 40N20. 2 No.	7.22	m^3	135.0	**974.70**
Reinforcement to pad fnd. 35kg/m^3	0.253	T	1 200.0	**303.60**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 2 No.	2.0	m^3	115.0	**230.00**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
Concrete - Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**
				Sub Total 71 378.75

Table 4.1.6: Option 2 Slimflor® beams and deep deck floor (un-propped)

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors				
PMF 210 Deep Deck 4 No. floors	2 352	m^2	45.0	**105 840.0**
Lightweight concrete infill grade 35N20 within deck 4 No. floors	100	m^3	128.0	**12 800.00**
T 16's @ 600mm c/c to bottom of each trough 3.1kg/m^2 4 No. floors	7.30	T	1 200.0	**8 760.00**
80mm deep lightweight concrete Grade 35N20 over deck 4 No. floors	188.0	m^3	128.0	**24 064.00**
Reinforcement to concrete floor over deck. A142 mesh 2.22kg/m^2 4 No. floors	2 352	m^2	6.5	**15 288.00**
Concrete - Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.00**
Precast concrete stairs 10/167.5mm risers 9/305mm treads	16	no.	4 000.0	**64 000.00**
Masonry				
215mm 5N hollow block inner leaf	965.0	m^2	40.0	**38 600.00**
100mm 5N brickwork outer leaf	1 321	m^2	95.0	**125 495.0**

Sub Total 397 927.00

Table 4.1.7: Option 2 Slimflor® beams and deep deck floor (un-propped)

Item Description	Quantity	Unit	Euro/unit	Total
Fire Protection				
Board to steel columns 22mm thick	135.77	m^2	45.0	**6 109.65**
Board to soffit of steel beams 22mm thick	215.0	m^2	45.0	**9 675.00**
Board to sides of steel beams within voids and lift shafts 22mm thick	70.0	m^2	45.0	**3 150.00**

Sub Total 18 934.65

Total 827 164.40

Table 4.1.8: Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)

Item Description	Quantity	Unit	Euro/unit	Total
Steelwork				
356 x 171 UB 45 grade 50	7.02	T	2 300.0	**16 146.00**
254 x 146 UB 43 grade 50	5.16	T	2 300.0	**11 868.00**
203 x 133 UB 30 grade 43	9.54	T	2 300.0	**21 942.00**
356 x 171 UB 51 Slimflor® grade 50	12.00	T	2 300.0	**27 600.00**
356 x 171 UB 45 Slimflor® grade 50	14.86	T	2 300.0	**34 178.00**
203 UC 86 grade 50	6.19	T	2 300.0	**14 237.00**
203 UC 71 Slimflor® grade 50	22.30	T	2 300.0	**51 290.00**
100 x 100 x 12 angle grade 43	5.27	T	2 300.0	**12 121.00**
203 UC 71 grade 50	3.33	T	2 300.0	**7 659.00**
203 UC 60 grade 50	5.63	T	2 300.0	**12 949.00**
203 UC 52 grade 50	3.14	T	2 300.0	**7 222.00**
203 UC 46 grade 50	7.40	T	2 300.0	**17 020.00**
400 x 400 x 35 base plate 27 No.	1.2	T	2 300.0	**2 760.00**
M20 bolts 150mm long	108	no.	40.0	**4 320.00**
Connections – bolts, end plates, cleats, welds etc.	10.19	T	2 300.0	**23 437.00**
Secondary steelwork	20.80	T	2 300.0	**47 840.00**
			Sub Total	**312 589.00**

Table 4.1.9: Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.3 x 2.3 x 1.1 pad foundation Grade 40N20. 5 No.	29	m^3	135.0	**3 915.00**
Reinforcement to pad fnd. 35kg/m^3	1.0	T	1 200.0	**1 200.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 5 No.	7.5	m^3	115.0	**862.50**
2.0 x 2.0 x 1.0 pad foundation Grade 40N20. 20 No.	80	m^3	135.0	**10 800.00**
Reinforcement to pad fnd. 35kg/m^3	2.8	T	1 200.0	**3 360.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 20 No.	22.0	m^3	115.0	**2 530.00**
1.9 x 1.9 x 1.0 pad foundation Grade 40N20. 2 No.	7.22	m^3	135.0	**974.70**
Reinforcement to pad fnd. 35kg/m^3	0.253	T	1 200.0	**303.60**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 2 No.	2.0	m^3	115.0	**230.00**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
Concrete – Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**

Sub Total 71 378.75

Table 4.1.10: Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors				
PMF 210 Deep Deck 7.5m span propped during construction 4 No. floors	2 352	m^2	45.0	**105 840.0**
Lightweight concrete infill grade 35N20 within deck 4 No. floors	100	m^3	128.0	**12 800.00**
T 16's @ 600mm c/c to bottom of each trough 3.1kg/m^2 4 No. floors	7.30	T	1 200.0	**8 760.00**
70mm deep lightweight concrete grade 35N20 over deck 4 No. floors	164.64	m^3	128.0	**21 073.92**
Reinforcement to concrete floor over deck. A142 mesh 2.22kg/m^2 4 No. floors	2 352	m^2	6.5	**15 288.00**
Concrete - Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.00**
Precast concrete stairs 10/167.5mm risers 9/305mm treads	16	no.	4 000.0	**64 000.00**
Masonry				
215mm 5N hollow block inner leaf	965.00	m2	40.0	**38 600.00**
100mm 5N brickwork outer leaf	1 321	m2	95.0	**125 495.0**

Sub Total 394 936.92

Table 4.1.11: Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)

Item Description	Quantity	Unit	Euro/unit	Total
Fire Protection				
Board to steel columns 22mm thick	136.5	m^2	45.0	**6 142.50**
Board to soffit of steel beams 22mm thick	146.20	m^2	45.0	**6 579.00**
Board to sides of steel beams within voids and lift shafts 22mm thick	70.0	m^2	45.0	**3 150.00**

Sub Total 15 871.50

Total 794 776.17

Table 4.1.12: Option 4 Composite Beams and Floor Slab

Item Description	Quantity	Unit	Euro/unit	Total
Steelwork				
305 x 165 UB 46 grade 50	7.73	T	2 300.0	**17 779.00**
305 x 165 UB 40 grade 50	7.68	T	2 300.0	**17 664.00**
305 x 102 UB 33 grade 50	17.63	T	2 300.0	**40 549.00**
305 x 102 UB 28 grade 50	5.38	T	2 300.0	**12 374.00**
254 x 102 UB 25 grade 50	10.20	T	2 300.0	**23 460.00**
203 x 133 UB 25 grade 50	1.80	T	2 300.0	**4 140.00**
100 x 100 x 12 angle grade 43	5.33	T	2 300.0	**12 259.00**
203 UC 71 grade 50	3.48	T	2 300.0	**8 004.00**
203 UC 60 grade 50	5.88	T	2 300.0	**13 524.00**
203 UC 52 grade 50	3.28	T	2 300.0	**7 544.00**
203 UC 46 grade 50	6.44	T	2 300.0	**14 812.00**
400 x 400 x 35 base plate	1.0	T	2 300.0	**2 300.00**
M20 bolts 150mm long	88	no.	40.0	**3 520.00**
Connections - bolts, end plates, cleats, welds, etc.	7.48	T	2 300.0	**17 204.00**
Secondary steelwork	20.80	T	2 300.00	**47 840.00**
			Sub Total	**242 973.00**

Table 4.1.13: Option 4 Composite Beams and Floor Slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.2 x 2.2 x 1.0 pad foundation Grade 40N20. 5 No.	24.2	m^3	135.0	**3 267.00**
Reinforcement to pad fnd. 35kg/m^3	0.847	T	1 200.0	**1 016.40**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 5 No.	6.7	m^3	115.0	**770.50**
1.9 x 1.9 x 1.0 pad foundation Grade 40N20. 22 No.	79.42	m^3	135.0	**10 721.70**
Reinforcement to pad fnd. 35kg/m^3	2.78	T	1 200.0	**3 336.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 22 No.	21.84	m^3	115.0	**2 511.60**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.6**
Concrete - Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**

Sub Total 68 826.15

Table 4.1.14: Option 4 Composite Beams and Floor Slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors				
55mm deep x 0.9mm thick Profiled steel deck 4 No. floors	2 352	m^2	35.0	**82 320.00**
Lightweight concrete infill grade 35N20 within deck 4 No. floors	71.0	m^3	128.0	**9 088.00**
T 16's @ 600mm c/c to bottom of each trough 6.2kg/m^2 4 No. floors	14.58	T	1 200.0	**17 496.00**
65mm deep lightweight concrete grade 35N20 over deck 4 No. floors	153	m^3	128.0	**19 584.00**
Reinforcement to concrete floor overdeck. A142 mesh 2.22kg/m^2 4 No. floors	2 352	m^2	6.5	**15 288.00**
19mm dia. x 100mm long Studs @ 300mm c/c 4 No. floors	2 850	no.	10.0	**28 500.00**
Concrete - Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.00**
Precast concrete stairs 11/159mm risers 10/275mm treads	16	no.	4 400.0	**70 400.00**
Masonry				
215mm 5N hollow block inner leaf	1 009	m^2	40.0	**40 360.00**
100mm 5N brickwork outer leaf	1 378	m^2	95.0	**13 0910.0**

Sub Total 417 026.00

Table 4.1.15: Option 4 Composite Beams and Floor Slab

Item Description	Quantity	Unit	Euro/unit	Total
Fire Protection				
Board to steel columns 22mm thick	142.72	m^2	45.0	**6 422.40**
Board to soffit of steel columns 22mm thick	134.20	m^2	45.0	**6 039.00**
Board to sides of steel beams within voids and lift shafts 22mm thick	70.00	m^2	45.0	**3 150.00**

Sub Total 15 611.40

Total 744 436.55

Table 4.1.16: Option 5   Cellular beams or castellated beams and composite slab

Item Description	Quantity	Unit	Euro/unit	Total
Steelwork				
457 x 191 UB 67 grade 50 castellated	39.8	T	2 500.0	**99 500.00**
406 x 140 UB 46 grade 50	13.25	T	2 300.0	**30 475.00**
305 x 165 UB 46 grade 50	7.73	T	2 300.0	**17 779.00**
305 x 165 UB 40 grade 43	1.92	T	2 300.0	**4 416.00**
305 x 102 UB 33 grade 50	1.98	T	2 300.0	**4 554.00**
305 x 102 UB 28 grade 50	1.34	T	2 300.0	**3 082.00**
254 x 102 UB 25 grade 50	3.60	T	2 300.0	**8 280.00**
203 x 133 UB 25 grade 43	1.80	T	2 300.0	**4 140.00**
100 x 100 x12 angle grade 43	5.43	T	2 300.0	**12 489.00**
254 UC 73 grade 50	7.77	T	2 300.0	**17 871.00**
203 UC 52 grade 50	6.32	T	2 300.0	**14 536.00**
203 UC 46 grade 50	4.90	T	2 300.0	**11 270.00**
400 x 400 x 35 baseplate 22No.	1.0	T	2 300.0	**2 300.00**
M20 bolts 150mm long	88	no.	40.0	**3 520.00**
Connections - bolts, end plates, cleats, welds, etc.	9.60	T	2 300.0	**22 080.00**
Secondary steelwork	20.80	T	2 300.00	**47 840.00**

Sub Total 304 132.00

Table 4.1.17: Option 5 Cellular beams or castellated beams and composite slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.3 x 2.3 x 1.1 pad foundation Grade 40N20. 22 No.	128.3	m^3	135.0	**17 320.50**
Reinforcement to pad fnd. 35kg/m^3	4.5	T	1 200.0	**5 400.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 22 No.	32.0	m^3	115.0	**3 680.00**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
Concrete - Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**
			Sub Total	**73 603.45**

Table 4.1.18: Option 5 Cellular beams or castellated beams and composite slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors				
55mm deep x 0.9mm thick Profiled steel deck 4 No. floors	2 352	m^2	37.0	**87 024.00**
Lightweight concrete infill grade 35N20 within deck 4 No. floors	71.0	m^3	128.0	**9 088.00**
T 16's @ 600mm c/c to bottom of each trough 6.2kg/m^2 4 No. floors	14.58	T	1 200.0	**17 498.88**
65mm deep lightweight concrete grade 35N20 over deck 4 No. floors	153.0	m^3	128.0	**19 584.00**
Reinforcement to concrete floor over deck. A142 mesh 2.22kg/m^2 4 No. floors	2 352	m^2	6.5	**15 288.00**
2/19mm dia. x 100mm long Studs @ 300mm c/c 4 No. floors	5 700	no.	10.0	**57 000.00**
Concrete - Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.00**
Precast concrete stairs 12/158mm risers 11/250mm treads	16	no.	4 800.0	**76 800.00**
Masonry				
215mm 5N hollow block inner leaf	1 083	m^2	40.0	**43 320.00**
100mm 5N brickwork outer leaf	1 491	m^2	95.0	**141 645.0**

Sub Total 470 327.88

Table 4.1.19: Option 5 Cellular beams or castellated beams and composite slab

Item Description	Quantity	Unit	Euro/unit	Total
Fire Protection				
Board to steel columns 22mm thick	70.94	m^2	45.0	**3 192.30**
Board to soffit of steel beams 22mm thick	154	m^2	45.0	**6 930.00**
Board to sides of steel beams within voids and lift shafts 22 mm thick	70	m^2	45.0	**3 150.00**

Sub Total 13 272.30

Total 861 335.63

Table 4.1.20: Option 6   Composite beams with web openings

Item Description	Quantity	Unit	Euro/unit	Total
Steelwork				
533 x 210 UB 82 grade 50 (11 No) (3 No. 250mm x 450mm opes/beam)	48.71	T	2 400.0	**116 904.0**
406 x 140 UB 46 grade 50	13.25	T	2 300.0	**30 475.00**
305 x 165 UB 46 grade 50	7.73	T	2 300.0	**17 779.00**
305 x 165 UB 40 grade 43	1.92	T	2 300.0	**4 416.00**
305 x 102 UB 33 grade 50	1.98	T	2 300.0	**4 554.00**
305 x 102 UB 28 grade 50	1.34	T	2 300.0	**3 105.00**
254 x 102 UB 25 grade 50	3.60	T	2 300.0	**8 280.00**
203 x 133 UB 25 grade 43	1.80	T	2 300.0	**4 140.00**
100 x 100 x 12 angle grade 43	5.41	T	2 300.0	**12 443.00**
254 UC 73 grade 50	7.67	T	2 300.0	**17 641.00**
203 UC 52 grade 50	6.24	T	2 300.0	**14 352.00**
203 UC 46 grade 50	4.83	T	2 300.0	**11 109.00**
400 x 400 x 35 baseplate 22No.	1.0	T	2 300.0	**2 300.00**
M20 bolts 150mm long	88	no.	40.0	**3 520.00**
Connections - bolts, end plates, cleats, welds, etc.	10.45	T	2 300.0	**24 035.00**
Secondary steelwork	20.80	T	2 300.00	**47 840.00**
				Sub Total 322 893.00

Table 4.1.21: Option 6 Composite beams with web openings

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.3 x 2.3 x 1.1 pad foundation Grade 40N20. 22 No.	128.1	m^3	135.0	**17 293.50**
Reinforcement to pad fnd. 35kg/m^3	4.49	T	1 200.0	**5 388.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 22 No.	32.0	m^3	115.0	**3 680.00**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
Concrete – Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**

Sub Total 73 564.45

Table 4.1.22: Option 6 Composite beams with web openings

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors				
55mm deep x 0.9mm thick Profiled steel deck 4 No. floors	2 352	m^2	37.0	**87 024.00**
Lightweight concrete infill grade 35N20 within deck 4 No. floors	71.0	m^3	128.0	**9 088.00**
T 16's @ 600mm c/c to bottom of each trough 6.2kg/m^2 4 No. floors	14.58	T	1 200.0	**17 498.88**
65mm deep lightweight concrete grade 35N20 over deck 4 No. floors	153	m^3	128.0	**19 584.00**
Reinforcement to concrete floor over deck. A142 mesh 2.22kg/m^2 4 No. floors	2 352	m^2	6.5	**15 288.00**
2/19mm dia. x 100mm long Studs @ 300mm c/c 4 No. floors	5 700	no.	10.0	**57 000.00**
Concrete - Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.00**
Precast concrete stairs 12/156mm risers 11/250mm treads	16	no.	4 800.0	**76 800.00**
Masonry				
215mm 5N hollow block inner leaf	1 068	m^2	40.0	**42 720.00**
100mm 5N brickwork outer leaf	1 471	m^2	95.0	**139 745.0**

Sub Total 467 827.88

Table 4.1.23: Option 6 Composite beams with web openings

Item Description	Quantity	Unit	Euro/unit	Total
Fire Protection				
Board to steel columns 22mm thick	70.08	m^2	45.0	**3 153.60**
Board to soffit of steel beams 22mm thick	156.5	m^2	45.0	**7 042.50**
Board to sides of steel beams within voids and lift shafts 22 mm thick	70.0	m^2	45.0	**3 150.00**

Sub Total 13 346.10

Total 877 631.43

Table 4.1.24: Option 7 Reinforced concrete flat slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
3.2 x 3.2 x 1.4 pad foundation Grade 40N20. 5 No.	71.68	m^3	135.0	**9 676.80**
Reinforcement to pad fnd. 35kg/m^3	2.5	T	1 200.0	**3 000.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 5 No.	14.0	m^3	115.0	**1 610.00**
3.0 x 2.6 x 1.2 pad foundation Grade 40N20. 20 No.	187.2	m^3	135.0	**25 272.00**
Reinforcement to pad fnd. 35kg/m^3	6.563	T	1 200.0	**7 875.60**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 20 No	43.0	m^3	115.0	**4 945.00**
2.3 x 2.3 x 1.0 pad foundation Grade 40N20. 4 No.	21.16	m^3	135.0	**2 856.60**
Reinforcement to pad fnd. 35kg/m^3	0.741	T	1 200.0	**889.20**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 4 No.	5.8	m^3	115.0	**667.00**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.0**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
300 x 1000 strip foundation to shear walls. Grade 40N20.	9.03	m^3	135.0	**1 219.05**
Reinforcement to strip fnd. 35kg/m^3	0.316	T	1 200.0	**379.20**
50mm lean mix concrete on 225mm min hardcore under strip foundation	8.30	m^3	115.0	**954.50**
				Sub Total 68 720.90

Table 4.1.25: Option 7 Reinforced concrete flat slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**
Concrete – Upper Floors				
300mm deep reinforced concrete flat slab. Grade 40N20 4 No. floors	706.0	m^3	135.0	**95 310.00**
Reinforcement to slab 200kg/m^3	141.00	T	1 200.0	**169 200.0**
Horizontal formwork to floor slab	2 352	m^2	65.0	**152 880.0**
Vertical formwork to floor slab	162.00	m^2	38.0	**6 156.00**
Secondary steelwork	20.80	T	2 300.0	**47 840.00**
500mm deep x 200mm wide reinforced conc. beam. Grade 40N20 4 No. beams	8.4	m^3	135.0	**1 134.00**
Reinforcement to beam 255kg/m^3	2.14	T	1 200.0	**2 568.00**
Horizontal formwork to beams	16.8	m^2	78.0	**1 310.40**
Vertical formwork to beams	84	m^2	78.0	**6 552.00**
600mm x 200mm reinforced concrete column. Grade 40N20 22 No. columns	37.10	m^3	160.0	**5 936.00**
Reinforcement to column 185kg/m^3	6.70	T	1 200.0	**8 040.00**
Vertical formwork to columns	494.56	m^2	90.0	**44 510.40**
400mm x 400mm reinforced concrete column. Grade 40N20 7 No. columns	15.74	m^3	160.0	**2 518.40**
Reinforcement to column 295kg/m^3	4.64	T	1 200.0	**5 568.00**
Vertical formwork to columns	157.36	m^2	90.0	**14 162.40**

Sub Total 601 512.20

Table 4.1.26: Option 7 Reinforced concrete flat slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors (Cont.)				
250mm reinforced concrete wall Grade 40N20	111.2	m^3	140.0	**15 568.00**
Reinforcement to wall 120kg/m^3	13.34	T	1 200.0	**16 008.00**
Vertical formwork to shear walls	896.55	m^2	46.0	**41 241.30**
Concrete - Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.0**
Precast concrete stairs 10/167.5mm risers 9/305mm treads	16	no.	4 000.0	**64 000.0**
Masonry				
215mm 5N hollow block inner leaf	1 185	m^2	40.0	**47 400.00**
100mm 5N brickwork outer leaf	1 322	m^2	95.0	**125 590.0**

Sub Total 312 887.30

Total 983 120.40

Table 4.1.27: Option 8 Pre-cast hollow core units on reinforced concrete edge beams

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.3 x 2.3 x 1.1 pad foundation Grade 40N20. 2 No.	11.64	m^3	135.0	**571.4**
Reinforcement to pad fnd. 35kg/m^3	0.407	T	1 200.0	**488.4**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 2 No.	2.9	m^3	115.0	**333.5**
3.2 x 2.9 x 1.3 pad foundation Grade 40N20. 20 No.	241.28	m^3	135.0	**32 572.80**
Reinforcement to pad fnd. 35kg/m^3	8.445	T	1 200.0	**10 134.00**
50mm lean mix concrete on 225mm min hardcore 20 No.	51.0	m^3	115.0	**5 865.00**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
300 x 1000 strip foundation to shear walls. Grade 40N20.	9.03	m^3	135.0	**1 219.05**
Reinforcement to strip fnd. 35kg/m^3	0.316	T	1 200.0	**379.20**
50mm lean mix concrete on 225mm min hardcore under strip foundation	8.30	m^3	115.0	**954.50**
Concrete – Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**

Sub Total 99 720.80

Table 4.1.28: Option 8 Pre-cast hollow core units on reinforced concrete edge beams

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors				
300mm deep reinforced conc. slab Grade 40N20 4 No. floors	36.00	m^3	135.0	**4 860.00**
Reinforcement to slab 120kg/m^3	4.32	T	1 200.0	**5 184.00**
Horizontal formwork to floor slab	120	m^2	65.0	**7 800.00**
Vertical formwork to floor slab	46.80	m^2	38.0	**1 778.40**
Secondary steelwork	20.80	T	2 300.0	**47 840.00**
400mm deep hollow core units 4 No. floors	2 232	m^2	90.0	**200 800.0**
75mm screed on hollow core units 4 No. floors	2 232	m^2	16.5	**36 828.00**
Reinforcement to screed A193 mesh. 3.02kg/m^2 4 No. floors	2 232	m^2	7.10	**15 847.20**
725mm deep x 500mm wide reinforced concrete L beam. Grade 40N20 4 No. beams	139.0	m^3	135.0	**18 765.00**
Reinforcement to L beam 195kg/m^3	27.1	T	1 200.0	**32 520.00**
Horizontal formwork to beams	246	m^2	78.0	**19 188.00**
Vertical formwork to beams	713.4	m^2	78.0	**55 645.20**
500mm deep x 200mm wide reinforced conc. beam. Grade 40N20 4 No. beams	8.40	m^3	135.0	**1 134.00**
Reinforcement to beam 265kg/m^3	2.14	T	1 200.0	**2 568.00**
Horizontal formwork to beams	16.80	m^2	78.0	**1 310.40**
Vertical formwork to beams	84.00	m^2	78.0	**6 552.00**
600mm x 300mm reinforced concrete column. Grade 40N20 20 No. columns	53.46	m^3	160.0	**8 553.60**

Sub Total 467 173.80

Table 4.1.29: Option 8   Pre-cast hollow core units on reinforced concrete edge beams

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors (cont.)				
Reinforcement to column 275kg/m^3	14.70	T	1 200.0	**17 640.00**
Vertical formwork to columns	534.60	m^2	90.0	**48 114.00**
400mm x 400mm reinforced concrete column. Grade 40N20 2 No. columns	4.75	m^3	160.0	**760.00**
Reinforcement to column 295kg/m^3	1.40	T	1 200.0	**1 680.00**
Vertical formwork to columns	47.52	m^2	90.0	**4 276.80**
250mm reinforced concrete wall Grade 40N20	117.60	m^3	140.0	**16 464.00**
Reinforcement to wall 120 kg/m^3	14.12	T	1 200.0	**16 944.00**
Vertical formwork to shear walls	948.15	m^2	46.0	**43 614.90**

Sub Total 149 493.70

Table 4.1.30: Option 8   Pre-cast hollow core units on reinforced concrete edge beams

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.00**
Precast concrete stairs 11/161mm risers 10/275mm treads	16	no.	4 400.0	**70 400.00**
Masonry				
215mm 5N hollow block inner leaf	1 102.39	m^2	40.0	**44 095.60**
100mm 5N brickwork outer leaf	1 396.64	m^2	95.0	**132 680.0**

Sub Total 250 255.60

Total 966 643.50

Table 4.1.31: Option 9 Reinforced concrete waffle slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.3 x 2.3 x 1.0 pad foundation Grade 40N20. 4 No.	21.16	m^3	135.0	**2 856.60**
Reinforcement to pad fnd. 35kg/m^3	0.741	T	1 200.0	**889.20**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 4 No.	5.8	m^3	115.0	**667.00**
3.0 x 2.6 x 1.2 pad foundation Grade 40N20. 20 No.	187.2	m^3	135.0	**25 272.00**
Reinforcement to pad fnd. 35kg/m^3	6.55	T	1 200.0	**7 860.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 20 No.	43.0	m^3	115.0	**4 945.00**
3.2 x 3.2 x 1.4 pad foundation Grade 40N20. 5 No.	71.68	m^3	135.0	**9 676.80**
Reinforcement to pad fnd. 35kg/m^3	2.51	T	1 200.0	**3 012.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 5 No.	14.1	m^3	115.0	**1 621.50**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
300 x 1000 strip foundation to shear walls. Grade 40N20.	9.03	m^3	135.0	**1 219.05**
Reinforcement to strip fnd. 35kg/m^3	0.316	T	1 200.0	**379.20**
50mm lean mix concrete on 225mm min hardcore under strip foundation	8.30	m^3	115.0	**954.50**

Sub Total 68 728.80

Table 4.1.32: Option 9 Reinforced concrete waffle slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**
Concrete – Upper Floors				
300mm deep reinforced concrete slab Grade 40N20 4 No. floors	36.0	m^3	135.0	**4 860.00**
Reinforcement to slab 120kg/m^3	4.32	T	1 200.0	**5 184.00**
Horizontal formwork to floor slab	120.00	m^2	65.0	**7 800.00**
Vertical formwork to floor slab	46.80	m^2	38.0	**1 778.40**
Secondary steelwork	20.80	T	2 300.0	**47 840.00**
400mm dp.waffle slab. Grade 40N 20 4 No. floors	626.0	m^3	135.0	**84 510.00**
Reinforcement to waffle slab 120kg/m^3	75.12	T	1 200.0	**90 144.00**
Formwork to waffle slab	2 232	m^2	100.0	**223 200.0**
500mm deep x 200mm wide reinforced conc. beam. Grade 40N20 4 No. beams	8.4	m^3	135.0	**1 134.00**
Horizontal formwork to beams	16.8	m^2	78.0	**1 310.40**
Vertical formwork to beams	84	m^2	78.0	**6552.00**
Reinforcement to beam 255kg/m^3	2.14	T	1 200.0	**2 568.00**
			Sub Total	**514 707.80**

Table 4.1.33: Option 9 Reinforced concrete waffle slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors (Cont.)				
600mm x 200mm reinforced concrete column. Grade 40N20 22 No. columns	38.15	m^3	160.0	**6 104.00**
Reinforcement to column 185kg/m^3	7.06	T	1 200.00	**8 472.00**
Vertical formwork to columns	508.64	m^2	90.0	**45 777.60**
400mm x 400mm reinforced concrete column. Grade 40N20 7 No. columns	16.18	m^3	160.0	**2 588.80**
Reinforcement to column 295kg/m^3	4.77	T	1 200.00	**5 724.00**
Vertical formwork to columns	161.84	m^2	90.0	**14 565.60**
250mm reinforced concrete wall Grade 40N20	114.40	m^3	140.0	**16 016.00**
Reinforcement to wall 120kg/m^3	13.73	T	1 200.0	**16 476.00**
Vertical formwork to shear walls	922.35	m^2	46.0	**42 428.10**
			Sub Total	**158 152.10**

Table 4.1.34: Option 9 Reinforced concrete waffle slab

Item Description	Quantity	Unit	Euro/unit	Total
Concrete - Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.00**
Precast concrete stairs 11/157mm risers 10/275mm treads	16	no.	4 400.0	**70 400.00**
Masonry				
215mm 5N hollow block inner leaf	1 185.4	m^2	40.0	**47 416.00**
100mm 5N brickwork outer leaf	1 359	m^2	95.0	**129 105.00**

Sub Total 250 001.00

Total 991 589.70

Table 4.1.35: Option 10 Precast double T units on reinforced concrete edge beams

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Sub Structure				
2.3 x 2.3 x 1.1 pad foundation Grade 40N20. 2No.	11.64	m^3	135.0	**1 571.40**
Reinforcement to pad fnd. 35kg/m^3	0.41	T	1 200.0	**492.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 2 No.	2.90	m^3	115.0	**333.50**
3.2 x 2.9 x 1.3 pad foundation Grade 40N20. 20 No.	241.28	m^3	135.0	**32 572.80**
Reinforcement to pad fnd. 35kg/m^3	8.44	T	1 200.0	**10 128.00**
50mm lean mix concrete on 225mm min hardcore under pad foundation. 20 No.	51.04	m^3	115.0	**5 869.60**
300 x 900 strip foundation to perimeter walls. Grade 40N20.	33.21	m^3	135.0	**4 483.35**
Reinforcement to strip fnd. 35kg/m^3	1.16	T	1 200.0	**1 392.00**
50mm lean mix concrete on 225mm min hardcore under strip foundation	30.44	m^3	115.0	**3 500.60**
300 x 1000 strip foundation to shear walls. Grade 40N20.	9.03	m^3	135.0	**1 219.05**
Reinforcement to strip fnd. 35kg/m^3	0.316	T	1 200.0	**379.20**
50mm lean mix concrete on 225mm min hardcore under strip foundation	8.30	m^3	115.0	**954.50**
Concrete – Ground Floor				
150mm deep floor slab Grade 40N20	97.2	m^3	135.0	**13 122.00**
Reinforcement to floor slab A142 mesh 2.22kg/m^2	648	m^2	6.5	**4 212.00**
50mm lean mix concrete on 225mm min hardcore under floor slab	178.2	m^3	115.0	**20 493.00**
			Sub Total	**100 723.00**

Table 4.1.36: Option 10 Precast double T units on reinforced concrete edge beams

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Upper Floors				
300mm deep reinforced concrete slab Grade 40N20 4 No. floors	36.00	m^3	135.0	**4 860.00**
Reinforcement to slab 120kg/m^3	4.32	T	1 200.0	**5 184.00**
Horizontal formwork to floor slab	120.0	m^2	65.0	**7 800.00**
Vertical formwork to floor slab	46.80	m^2	38.0	**1 778.40**
Secondary steelwork	20.80	T	2 300.0	**47 840.00**
500mm deep precast double T units 4 No. floors	2 232	m^2	70.0	**156 240.0**
75mm screed on precast units 4 No. floors	2 232	m^2	16.5	**36 828.00**
Reinforcement to screed A193 mesh. 3.02kg/m^2 4 No. floors	2 232	m^2	7.10	**15 847.20**
825mm deep x 500mm wide reinforced concrete L beam Grade 40N20 4 No. beams	158.68	m^3	135.0	**21 421.80**
Reinforcement to L beam 195kg/m^3	31.0	T	1 200.0	**37 200.00**
Horizontal formwork to beams	246.0	m^2	78.0	**19 188.00**
Vertical formwork to beams	811.8	m^2	78.0	**63 320.40**
500mm deep x 200mm wide reinforced conc.beam. Grade 40N20 4 No. beams	8.40	m^3	135.0	**1 134.00**
Reinforcement to beam 255kg/m^3	2.14	T	1 200.0	**2 568.00**
Horizontal formwork to beams	16.80	m^2	78.0	**1 310.40**
Vertical formwork to beams	84.00	m^2	78.0	**6 552.00**
600mm x 300mm reinforced concrete column. Grade 40N20 20 No. columns	54.90	m^3	160.0	**8 784.00**

Sub Total 437 856.20

Table 4.1.37: Option 10 Precast double T units on reinforced concrete edge beams

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Floor (cont.)				
Reinforcement to column 275kg/m^3	15.10	T	1 200.00	**18 120.00**
Vertical formwork to columns	549.0	m^2	90.00	**49 410.00**
400mm x 400mm reinforced concrete column. Grade 40N20 2 No. columns	4.88	m^3	160.0	**780.80**
Reinforcement to column 295kg/m^3	1.44	T	1 200.0	**1 728.00**
Vertical formwork to columns	48.80	m^2	90.0	**4 392.00**
250mm reinforced concrete wall Grade 40N20	120.8	m^3	140.0	**16 912.00**
Reinforcement to wall 120 kg/m^3	14.50	T	1 200.0	**17 400.00**
Vertical formwork to shear walls	974.0	m^2	46.0	**44 804.00**
			Sub Total	**153 546.80**

Table 4.1.38: Option 10 Precast double T units on reinforced concrete edge beams

Item Description	Quantity	Unit	Euro/unit	Total
Concrete – Stairs				
Precast concrete half landing 1 100mm wide x 2 400mm long	8	no.	385.0	**3 080.00**
Precast concrete stairs 12/152mm risers 11/250mm treads	16	no.	4 800.0	**76 800.00**
Masonry				
215mm 5N hollow block inner leaf	1 102.4	m^2	40.0	**44 096.00**
100mm 5N brickwork outer leaf	1 434.3	m^2	95.0	**136 258.5**
			Sub Total	**260 234.50**
			Total	**952 360.50**

Tables 4.1.39 and 4.1.40 show the summary of cost of the various structural elements within each of the structural alternatives. This is presented graphically in Figure 4.1.1.

Table 4.1.39: Costs (Dublin - euro) **(Total Area 2,592m^2)**

STRUCTURAL OPTION	Steelwork	Sub-struct. & Ground Floor	Upper Floors	Stairs
Option 1 Slimflor® beams and pre-cast hollow core slab	318 937.00	71 378.75	89 672.00	67 080.00
Option 2 Slimflor® beams and deep deck floor (un-propped)	338 924.00	71 378.75	166 752.00	67 080.00
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	312 589.00	71 378.75	163 761.92	67 080.00
Option 4 Composite beams and floor slab	242 973.00	68 826.15	172 276.00	73 480.00
Option 5 Cellular beams or castillated beams and composite slab	304 132.00	73 603.45	205 482.88	79 880.00
Option 6 Composite beams with web openings	322 893.00	73 564.45	205 482.88	79 880.00
Option 7 Reinforced concrete flat slab	47 840.00	106 547.90	264 510.00	67 080.00
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	47 840.00	99 720.80	263 519.20	73 480.00
Option 9 Reinforced concrete waffle slab	47 840.00	106 555.80	184 698.00	73 480.00
Option 10 Pre-cast double T units on reinforced concrete edge beams	47 840.00	100 723.00	218 959.20	79 880.00

Table 4.1.40: Costs (Dublin - euro) **(Total Area 2,592m²)**

STRUCTURAL OPTION	Formwork	Conc.Walls Beams & Columns	Fire Protection	Masonry
Option 1 Slimflor® beams and pre-cast hollow core slab	______	_______	18 787.50	158 220.00
Option 2 Slimflor® beams and deep deck floor (un-propped)	______	_______	18 934.65	164 095.00
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	______	_______	15 871.50	164 095.00
Option 4 Composite beams and floor slab	_______	_______	15 611.40	171 270.00
Option 5 Cellular beams or castillated beams and composite slab	______	______	13 272.30	184 965.00
Option 6 Composite beams with web openings	______	_______	13 346.10	182 465.00
Option 7 Reinforced concrete flat slab	266 812.00	57 340.00	______	172 990.00
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	188 279.70	117 028.60	______	176 775.60
Option 9 Reinforced concrete waffle slab	343 412.10	59 082.80	______	176 521.00
Option 10 Pre-cast double T units on reinforced concrete edge beams	198 555.20	126 048.60	______	180 354.50

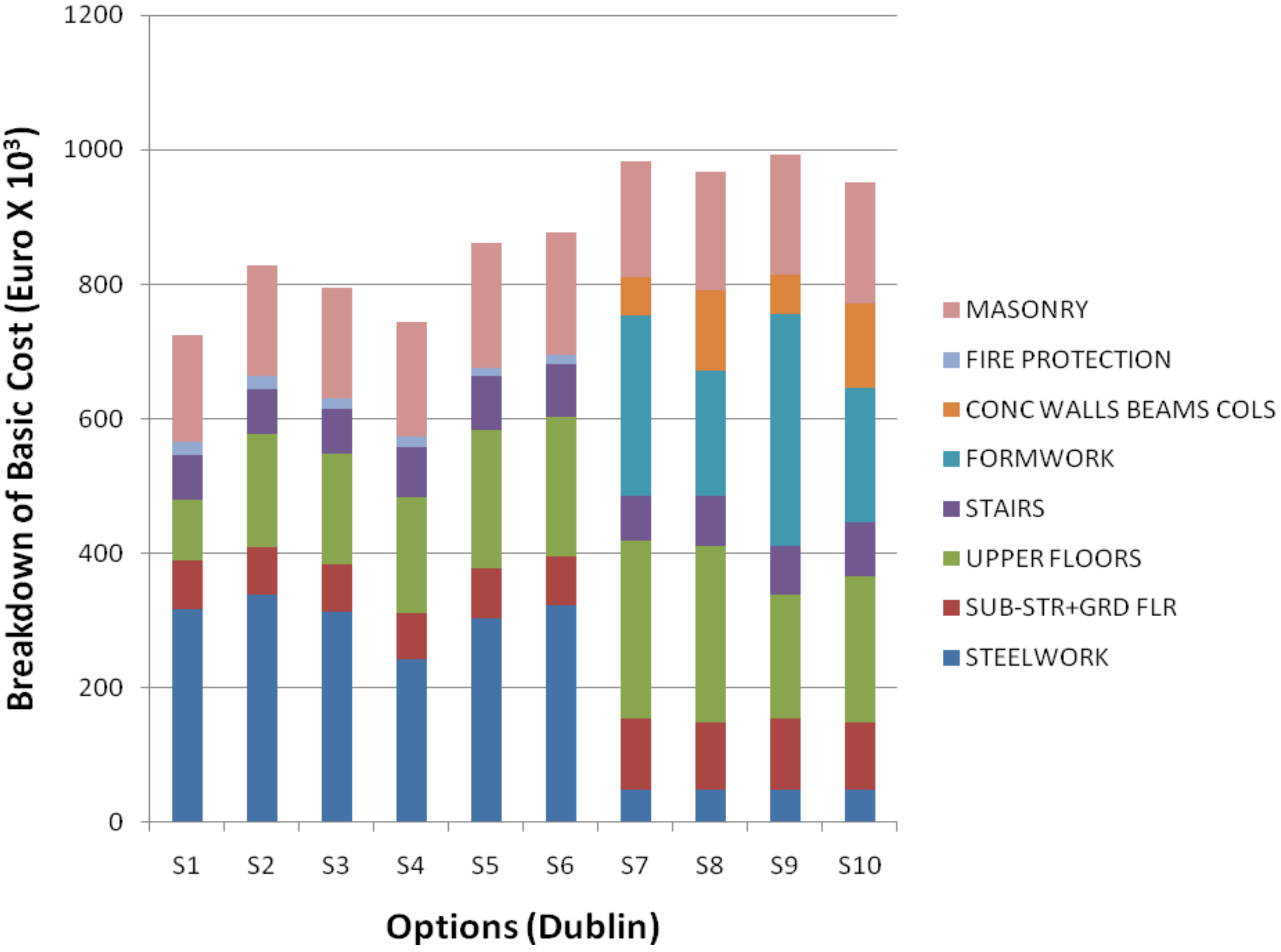

Figure 4.1.1 Breakdown of material costs in Dublin (euro)

Table 4.1.41 represents the total cost in euro of each of the 10 structural options, excluding preliminaries and contingencies.

Table 4.1.41: Summary of costs (Dublin - euro) (Total Area 2,592m^2)

STRUCTURAL OPTION	TOTAL STRUCTURAL COST (EURO)
Option 1 **Slimflor® beams and pre-cast hollow core slab**	**724 075.25 (1st)**
Option 2 **Slimflor® beams and deep deck floor (un-propped)**	**827 164.40 (4th)**
Option 3 **Slimflor® beams and deep deck floor (propped 7.5m span)**	**794 776.17 (3rd)**
Option 4 **Composite beams and floor slab**	**744 436.55 (2nd)**
Option 5 **Cellular beams or castillated beams and composite slab**	**861 335.63 (5th)**
Option 6 **Composite beams with web openings**	**877 631.43 (6th)**
Option 7 **Reinforced concrete flat slab**	**983 120.80 (9th)**
Option 8 **Pre-cast hollow core units on reinforced concrete edge beams**	**966 643.50 (8th)**
Option 9 **Reinforced concrete waffle slab**	**991 589.70 (10th)**
Option 10 **Pre-cast double T units on reinforced concrete edge beams**	**952 360.50 (7th)**

The cheapest options in terms of structure only are:

- Slimflor® beams and pre-cast hollow core slab (724,075.21 euro)
- Composite beam and floor slab (744,436.55 euro)

The most expensive options in terms of structure only are:

- Reinforced concrete flat slab (991,589.70 euro)
- Reinforced concrete waffle slab (983,120.80 euro)

Tables 4.1.42 and 4.1.43 show the total elemental costs and the costs per square metre of the gross floor area (2,592m^2) for each of the structural options. Main contractors' preliminaries are applied to the building elements at a rate ranging from 6.3% to 7.8% of the basic cost. The variation is due to the time related items that would be affected by the different construction periods of each option. The preliminaries could possibly change the cost ranking of the structural forms. A contingency sum of 7.5% of the basic cost plus preliminaries is also added. This information is provided by Cormac Construction, Dublin.

This information is presented graphically in Figure 4.1.2.

A definition of preliminaries and contingencies, which form part of the Bill of Quantities, is set out below:

Preliminaries are matters which feature at the beginning of a Bill of Quantities, which are relevant to the contractor in terms of his obligations and responsibilities and which will therefore influence his costings. These include such items as names of clients and consultants, insurance requirements, length of contract, descriptions of the site in terms of its access, working areas and adjacent buildings etc., a detailed description of the work to be undertaken and the order in which it should be tackled. They are added to the basic cost and are represented as a percentage of that basic cost.

Contingencies is a sum set aside to cover the cost of any additional or un-foreseen work which may be encountered once the project proceeds on site. Contingencies are also used to pay for changes which a client may request or meet extra payments which the contractor may be entitled to. Contingencies are valued as a percentage of the total basic cost plus preliminaries and added on to the billed items.

Table 4.1.42: Elemental costs/m^2 (Dublin – Euro/m^2) (Total Area 2,592m^2)

STRUCTURAL OPTION	Sub-struct. & Grd. Floor	Upper Floors & Frame	Stairs	External Walls	Sub Total
Option 1 **Slimflor® beams and pre-cast hollow core slab**	27.54	164.89	25.88	61.04	**279.35 (1st)**
Option 2 **Slimflor® beams and deep deck floor (un-propped)**	27.54	202.40	25.88	63.31	**319.13 (4th)**
Option 3 **Slimflor® beams and deep deck floor (propped 7.5m span)**	27.54	189.90	25.88	63.31	**306.63 (3rd)**
Option 4 **Composite beams and floor slab**	26.55	166.23	28.35	66.08	**287.21 (2nd)**
Option 5 **Cellular beams or castillated beams and composite slab**	28.40	201.73	30.82	71.36	**332.31 (5th)**
Option 6 **Composite beams with web openings**	28.40	209.00	30.82	70.40	**338.60 (6th)**
Option 7 **Reinforced concrete flat slab**	41.11	245.56	25.88	66.74	**379.30 (9th)**
Option 8 **Pre-cast hollow core units on reinforced concrete edge beams**	38.86	237.91	28.35	68.20	**372.93 (8th)**
Option 9 **Reinforced concrete waffle slab**	41.10	245.00	28.35	68.10	**382.55 (10th)**
Option 10 **Pre-cast double T units on reinforced concrete edge beams**	38.86	228.16	30.82	69.58	**367.42 (7th)**

Table 4.1.43: Elemental costs/m^2 (Dublin – Euro/m^2) (Total Area 2,592m^2)

STRUCTURAL OPTION	Prelimins (6.3% - 7.8%)	Sub Total	Contings. (7.5%)	Total Cost Per m^2
Option 1 Slimflor® beams and pre-cast hollow core slab	18.16 (6.5%)	**297.51**	22.31	**319.82 (1st)**
Option 2 Slimflor® beams and deep deck floor (un-propped)	20.10 (6.3%)	**339.23**	25.44	**364.67 (4th)**
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	19.93 (6.5%)	**326.56**	24.49	**351.05 (3rd)**
Option 4 Composite beams and floor slab	18.96 (6.6%)	**306.17**	22.96	**329.13 (2nd)**
Option 5 Cellular beams or castillated beams and composite slab	21.27 (6.4%)	**353.59**	26.52	**380.11 (5th)**
Option 6 Composite beams with web Openings	21.67 (6.4%)	**360.27**	27.02	**387.29 (6th)**
Option 7 Reinforced concrete flat slab	28.83 (7.6%)	**408.13**	30.61	**438.74 (9th)**
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	28.00 (7.5%)	**400.93**	30.07	**431.00 (8th)**
Option 9 Reinforced concrete waffle slab	29.84 (7.8%)	**412.37**	30.93	**443.30 (10th)**
Option 10 Pre-cast double T units on reinforced concrete edge beams	27.56 (7.5%)	**394.98**	29.62	**424.60 (7th)**

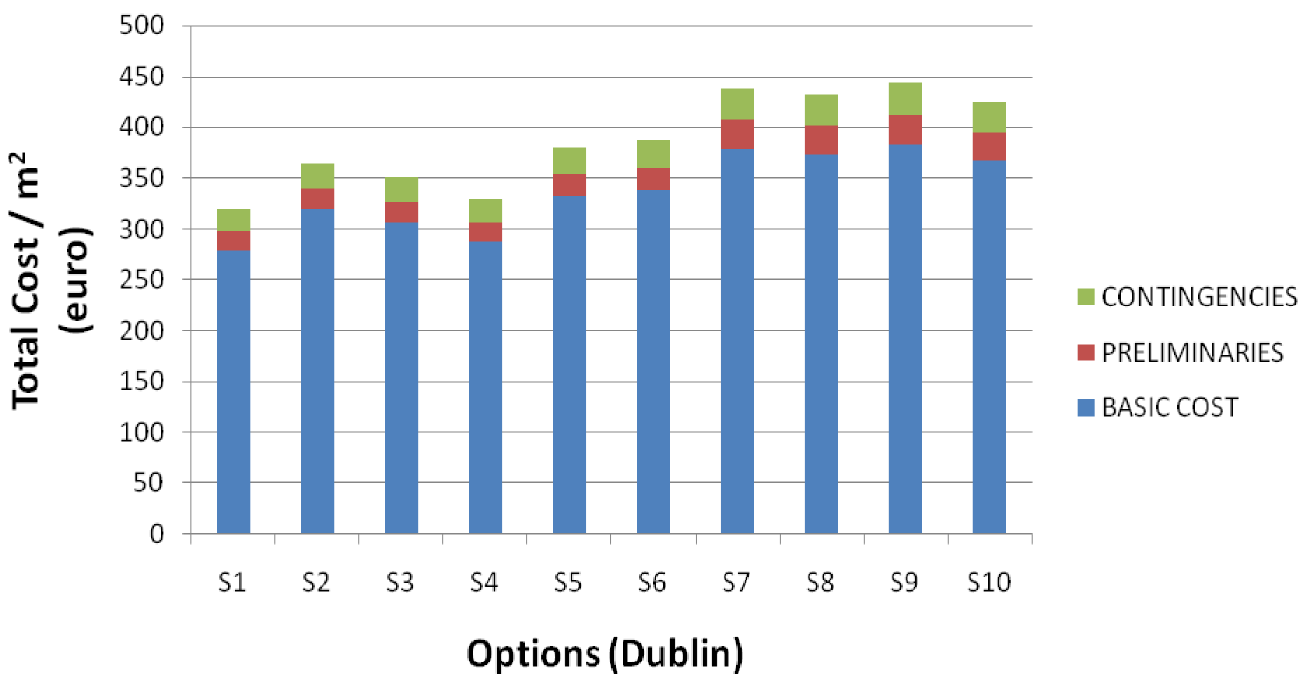

Figure 4.1.2 Total elemental costs /m^2 - Dublin (Area = 2,592m^2)

The ranking of the 10 options per square metre on the basis of cost including preliminaries and contingencies is:

1^{st}	**Option 1**	**319.82 euro**	(Slimflor® beams and pre-cast hollow core slab)
2^{nd}	**Option 4**	**329.13 euro**	(Composite beams and composite floor slab)
3^{rd}	**Option 3**	**351.05 euro**	(Slimflor® beams and deep deck floor propped)
4^{th}	**Option 2**	**364.67 euro**	(Slimflor® beams and deep deck floor un-propped)
5^{th}	**Option 5**	**380.11 euro**	(Cellular beams or castellated beams and composite slab)
6^{th}	**Option 6**	**387.29 euro**	(Composite beams with web openings)
7^{th}	**Option 10**	**424.60 euro**	(Precast double T units on reinforced concrete edge beams)
8^{th}	**Option 8**	**431.00 euro**	(Pre-cast hollow core units on R.C. edge beams)
9^{th}	**Option 7**	**438.74 euro**	(Reinforced concrete flat slab)
10^{th}	**Option 9**	**443.30 euro**	(Reinforced concrete waffle slab)

There is a significant variation in structure cost between the steel and concrete structural forms. The above information shows all steel options are cheaper than the concrete alternatives with a difference of 32.7% between the least expensive steel form and the least expensive concrete option. This represents a structural cost difference of 104.78 euro per square metre or 271,589.76 euro in total. The variation between the least expensive and most expensive structural form is 38.6% which is equivalent to 123.48 euro per square metre or 320,060.16 euro in total.

An examination of the element summary (Table 4.1.42) shows that the cost of the sub-structure and ground floor for the concrete solutions is on average 44% more than the cost for the steelwork options. The difference in cost for these two elements between the least expensive (composite beams and floor slab) and most expensive (reinforced concrete waffle slab) is 54.8%. Concrete is substantially heavier than steel and therefore transmits larger loads to the foundations. For example, the 300mm deep concrete flat slab in option 7, which has a density of $24kN/m^3$, weighs $7.2kN/m^2$. The 210mm deep deck floor in option 3 weighs $2.0kN/m^2$. It is made up of lightweight concrete infill and 70mm lightweight concrete slab over with a concrete density of $18kN/m^3$,.

The average cost difference on the sub-structure and ground floor increases when preliminaries are added. The concrete options require the ground floor slab to be constructed before commencement of the upper floors. The slab is required for propping of formwork to the suspended floors. As a result, the construction programme is pushed out and this is reflected in the preliminaries of 7.5% to 7.8% for the concrete structures and 6.3% to 6.6% for the steel structures.

The higher cost of the upper floors in the concrete options is reflected in the labour, materials and time required for steel fixing, pouring of concrete and striking of formwork. The variation in price for the pre-cast stairs and external walls is 19%. This cost difference is due to the overall height of the building and is therefore a function of the floor type selected. As previously explained in Chapter 3, the height of the vertical elements depends on the depth of the floor zone which is different for each of the structural options and is not solely dependent on whether the structural form is steel or concrete.

The variation in cost between the least and most expensive options, excluding preliminaries and contingencies, is 36.9%. If these items are taken into account the difference is 38.6%. Again this variation of 1.7% represents the time related savings on the steelwork construction as assigned by Cormac Construction. In this study the ranking of the options in terms of cost, excluding preliminaries and contingencies, does not change when they are added to the basic cost.

A comparison of the basic cost, excluding preliminaries and contingencies, between the slimflor℗ beams and deep deck floor propped (794,776.17euro) and the slimflor℗ beams and deep deck floor un-propped (827,164.40euro) is useful. There is an overall saving of 4.1% on the deep deck floor propped. The cost of the sub-structure and ground floor, stairs and masonry does not change. The cost saving on the steelwork, upper floor deck and fire protection is due to the use of smaller steel sections and less concrete infill to the deep deck. This is made possible when the floor is propped during construction. The preliminaries applied to the deep deck floor propped are only 0.2% greater than the value given to the deep deck floor un-propped. The extra time and labour involved in propping has very little effect on the overall cost.

The difference in cost, including preliminaries and contingencies, between the least and most expensive steel alternatives is 21%. The variation within the concrete options is only 4.4%. The difference between the most expensive steel option (composite beams with web openings) and the least expensive concrete form (pre-cast double T units on reinforced concrete edge beams) is 9.6%. This is quite significant when considering that it represents an overall variation of 96,707.0 euro.

The conclusion of the cost study would indicate that the steelwork options are significantly cheaper than the concrete alternatives with option 1 (Slimflor℗ beams and pre-cast hollow core slab) being the preferred structural solution in terms of cost.

4.2 Initial Embodied Energy

4.2.1 Introduction

Embodied energy in building materials has been studied for the past several decades by researchers interested in the relationship between building materials, construction processes, and their environmental impacts (Canadian Architect, 1997). The amount of embodied energy in buildings varies considerably. Embodied energy consumption depends on the nature of the building, the materials used and the source of these materials. This is why data for a building material in one country may differ significantly from the same material in another country.

There are two forms of embodied energy in buildings:

- Initial embodied energy
- Recurring embodied energy

The initial embodied energy is the total energy consumed by all the processes associated with the production of a product. For a building material, this represents the energy used in the extraction of materials, their processing, manufacture and transportation.

This initial embodied energy has two components:

Direct energy the energy used to transport building products to the site and then to construct the building; and

Indirect energy the energy used to acquire, process and manufacture the building materials, including any transportation related to these activities.

Recurring embodied energy in buildings represents the non-renewable energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building.

Typically, embodied energy is measured as a quantity of non-renewable energy per unit of building material, component or system. For example, it may be expressed as megajoules (MJ) or gigajoules (GJ) per unit weight or area. The amount of embodied energy in buildings varies considerably. Initial embodied energy consumption depends on the nature and location of the building, the materials used and the source of these materials. Data for a building material in one country may differ significantly from the same material manufactured in another country. This is due to a number of reasons such as accessibility, method of transportation, distance between source of material and site, methods of processing etc. (Canadian Architect 2007).

Structural steel and concrete framed structures are two of the most widely used options for Irish commercial buildings (SCI 1993). As the steel and concrete industries are also two of the most energy intensive manufacturing industries in the world (Price,L et al, 2002) the embodied energy of these structural options should be of interest to designers due to their impact on the global environment.

The main processes in primary steel-making are mining of raw materials, carbonisation of blended coal to produce coke, extraction of iron from ore in a reduction process, processing of molten iron to produce steel, casting, rolling and shaping. The reduction of iron ore is the most energy intensive stage of the steel making process. Steel is used in considerable mass in construction and there is concern about its relatively high embodied energy emissions compared with those of alternative construction materials (SCI 1994).

The study addresses and compares the initial embodied energy of the ten structural design options, previously analysed for cost, in terms of production, transportation and construction. In the same way, the assessment of the ten structural forms is carried out in relation to the structure only and does not include the non variable items of the roof, mechanical and electrical works, windows and doors, internal walls and partitions, floor and ceiling finishes, sanitary and general fittings.

The methodology involved in computing the initial embodied energy of each of the structural frame options is to:

- Calculate the weight of the materials in terms of kg or tonne
- Calculate the number of trips required to transport the materials to site
- Calculate the distance in km from the material source point to site (road and sea)
- Determine the energy intensities/coefficients of the various materials required for each of the ten structural options with regard to production, transportation and construction.
- Apply these energy intensity values to the materials.

The aim of this section of the thesis is to:

- Determine the initial embodied energy for each of the ten structural forms in relation to production, transportation and construction
- Tabulate the values showing a comparison amongst the structural forms
- Draw up a bar chart showing separately the initial embodied energy due to production, transportation and construction.

In 2006 the Inventory of Carbon and Energy (ICE) was published by Professor Geoff Hammond and Craig Jones of the University of Bath, UK. The aim of this work was to create an inventory of building materials with values of embodied energy and carbon coefficients. The data was collected from books, reports, conference papers, web searches etc. To aid in the selection of “best” coefficients it was required to set up a database (ICE-Database) that stored relevant information from the literature (i.e. country of data, year, data source, specific comments etc.). This inventory was classified by over 30 main material groups (i.e. aggregates, aluminium etc.) and a material profile was created for each of the main materials.

This study uses the coefficients/energy intensities tabulated in this inventory for the production of all materials.

4.2.2 Initial Embodied Energy Analysis Model

The calculations for obtaining initial embodied energies for the steel and concrete options considered in this study in relation to production, transportation and construction are based on Acquaye, A, Duffy, A, and Basu, B ,2007 paper "Comparative Embodied Energy Analysis of a Steel and Concrete Structural System in Ireland".

The total initial embodied energy is given as:

$E_e = E_p + E_t + E_c$

Where

E_p = Energy due to production of the material

E_t = Energy due to transportation of material

E_c = Energy due to construction

i) Energy due to the production of the material

The initial embodied energy values for material production in Ireland are obtained from the Inventory of Carbon and Energy (ICE) 2006. This inventory contains both embodied energy (initial and recurring) and carbon data for various materials used in the building industry.

Assuming a waste factor of 5% for steel during production of structural sections (Chen *et al*) the initial embodied energy is given as;

$E_p = 1.05 e_i QA$

Where

Q = quantity of steel (kg/m^2)

A = total floor area of building (m^2)

e_i = energy intensity of steel production (MJ/kg)

The initial embodied energy in all other building materials is given as;

$E_p = \%_w e_i QA$

Where

$\%_w$ = assumed waste factor of material

Q = quantity of the material/m^2

e_i = energy intensity of material production in Ireland (MJ/kg)

A = total floor area of building (m^2)

Sample calculations for obtaining the initial embodied energy of the structural steelwork frame and columns, concrete foundations, hardcore and masonry in relation to production for structural option 6, composite beams with web openings, are set out below. All weights of material are taken from the Bill of Quantities drawn up for this structural option (Tables 4.1.20 to 4.1.23). The total area of the building is 2,592m^2.

a) Steelwork

E_p (production of the material)	=	$1.05e_iQA$		
Total weight of steelwork	=	136730 kg		
Weight/m^2 Q	=	136730/2592 kg/m^2	=	52.75 kg/m^2
Energy intensity coefficient e_i	=	25.50MJ/kg		
Therefore				
E_p (production of the material)	=	(1.05)x(25.5)x(52.75)x(2 592)	=	3,660,950 MJ
			=	3,660.95 GJ

b) Concrete Foundations

E_p (production of the material)	=	$\%_w e_iQA$		
Total weight of concrete	=	387,624 kg		
Weight/m^2 Q	=	387 624/2 592 kg/m^2	=	149.54kg/m^2
% reinforcement	=	0.45%		
Energy intensity coefficient e_i	=	1.50MJ/kg		
Material waste factor	=	2.5%		
Therefore				
E_p (production of the material)	=	(1.025)x(1.5)x(149.54)x(2 592)	=	595,935 MJ
			=	595.935 GJ

c) Hardcore

E_p (production of the material)	=	$\%_w e_iQA$		
Total weight of hardcore	=	107,310 kg		
Weight/m^2 Q	=	107,310/2 592 kg/m^2	=	41.40kg/m^2
Energy intensity coefficient e_i	=	0.40MJ/kg		
Material waste factor	=	2.5%		
Therefore				
E_p	=	(1.025)x(0.4)x(41.40)x(2 592)	=	43,996.608 MJ
			=	44.00 GJ

d) Masonry

Blockwork

E_p (production of the material)	=	$\%_w e_i QA$		
Total weight of blockwork	=	344,430 kg		
Weight/m^2 Q	=	344,430/2 592 kg/m^2	=	132.88kg/m^2
Energy intensity coefficient e_i	=	3.0 MJ/kg		
Material waste factor	=	5.0%		
Therefore				
E_p (production of the material)	=	(1.05)x(3.0)x(132.88)x(2 592)	=	1,084,938.62 MJ
	=		=	1,084.94 GJ

Brickwork

E_p (production of the material)	=	$\%_w e_i QA$		
Total weight of brickwork	=	323620 kg		
Weight/m^2 Q	=	323,620/2,592 kg/m^2	=	124.85 kg/m^2
Energy intensity coefficient e_i	=	8.2 MJ/kg		
Material waste factor	=	5.0%		
Therefore				
E_p (production of the material)	=	(1.05)x(8.2)x(124.85)x(2592)	=	2,786,292.43 MJ
	=	2,786.3 GJ		

Total initial embodied energy of masonry	=	(1,084.94 + 2,786.3) GJ
	=	3,871 GJ

The initial embodied energy for the material production of the structural elements of each of the 10 building forms is shown in Tables 4.2.2.1 – 4.2.2.4 and presented graphically in Figure 4.2.2.1

Table 4.2.2.1: Initial Embodied Energy (Dublin -GJ) (Total Area 2,592m^2)

STRUCTURAL OPTION	In-situ concrete slab	Precast slab & Stairs	Structural steelwork	Floor screed
Option 1 Slimflor® beams and pre-cast hollow core slab	_____	1 587.27	3 662.82	_____
Option 2 Slimflor® beams and deep deck floor (un-propped)	_____	54.00	3 896.03	520.29
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	_____	54.00	3 588.65	455.64
Option 4 Composite beams and floor slab	_____	54.00	2 787.35	423.40
Option 5 Cellular beams or castillated beams and composite slab	_____	54.60	3 406.85	423.40
Option 6 Composite beams with web Openings	_____	54.00	3 660.95	423.40
Option 7 Reinforced concrete flat slab	4 550.31	54.00	556.92	_____
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	186.00	2 058.00	556.92	630.00
Option 9 Reinforced concrete waffle slab	3 319.92	54.00	556.92	_____
Option 10 Pre-cast double T units on reinforced concrete edge beams	186.00	1 554.60	556.92	630.00

Table 4.2.2.2: Initial Embodied Energy (Dublin - GJ) **(Total Area 2,592m^2)**

STRUCTURAL OPTION	Steel deck profiled	Concrete infill	Foundations & Grd. Floor	Concrete beams
Option 1 Slimflor® beams and pre-cast hollow core slab	_____	108.24	910.06	_____
Option 2 Slimflor® beams and deep deck floor (un-propped)	1 768.23	333.94	910.06	_____
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	1 768.23	333.94	910.06	_____
Option 4 Composite beams and floor slab	1 326.93	349.76	863.59	_____
Option 5 Cellular beams or castillated beams and composite slab	1 326.93	349.76	954.61	_____
Option 6 Composite beams with web Openings	1 326.93	349.76	954.61	_____
Option 7 Reinforced concrete flat slab	_____	_____	1 547.97	62.00
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	_____	_____	1 447.87	958.00
Option 9 Reinforced concrete waffle slab	_____	_____	1 547.97	62.00
Option 10 Pre-cast double T units on reinforced concrete edge beams	_____	_____	1 447.87	1 084.64

Table 4.2.2.3: Initial Embodied Energy (Dublin - GJ) **(Total Area 2,592m²)**

STRUCTURAL OPTION	Concrete columns	Concrete shear wall	Formwork	Fire protection
Option 1 Slimflor® beams and pre-cast hollow core slab	_____	_____	_____	122.75
Option 2 Slimflor® beams and deep deck floor (un-propped)	_____	_____	_____	123.69
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	_____	_____	_____	103.74
Option 4 Composite beams and floor slab	_____	_____	_____	102.00
Option 5 Cellular beams or castillated beams and composite slab	_____	_____	_____	86.73
Option 6 Composite beams with web Openings	_____	_____	_____	87.36
Option 7 Reinforced concrete flat slab	362.45	574.46	1 092.00	_____
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	451.56	607.52	678.30	_____
Option 9 Reinforced concrete waffle slab	372.54	591.00	1 611.46	_____
Option 10 Pre-cast double T units on reinforced concrete edge beams	463.80	624.0	713.40	_____

Table 4.2.2.4: Initial Embodied Energy (Dublin – GJ) (Total Area 2,592m²)

STRUCTURAL OPTION	Lean mix to Fnds. & Grd. Floor	Hardcore to Fnds. & Grd. Floor	Masonry	Total
Option 1 Slimflor® beams and pre-cast hollow core slab	86.96	169.16	3 352.70	**9 999.96 (2nd)**
Option 2 Slimflor® beams and deep deck floor (un-propped)	86.96	169.16	3 480.63	**11 342.99 (6th)**
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	86.96	169.16	3 480.63	**10 951.01 (4th)**
Option 4 Composite beams and floor slab	85.92	167.09	3 635.60	**9 795.64 (1st)**
Option 5 Cellular beams or castillated beams and composite slab	87.18	169.53	3 924.40	**10 783.99 (3rd)**
Option 6 Composite beams with web Openings	87.18	169.53	3 871.00	**10 984.72 (5th)**
Option 7 Reinforced concrete flat slab	101.34	197.03	3 707.72	**12 806.20 (10th)**
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	98.12	190.68	3765.50	**11 628.47 (8th)**
Option 9 Reinforced concrete waffle slab	101.38	197.13	3 778.63	**12 192.94 (9th)**
Option 10 Pre-cast double T units on reinforced concrete edge beams	98.10	190.82	3 837.32	**11 387.47 (7th)**

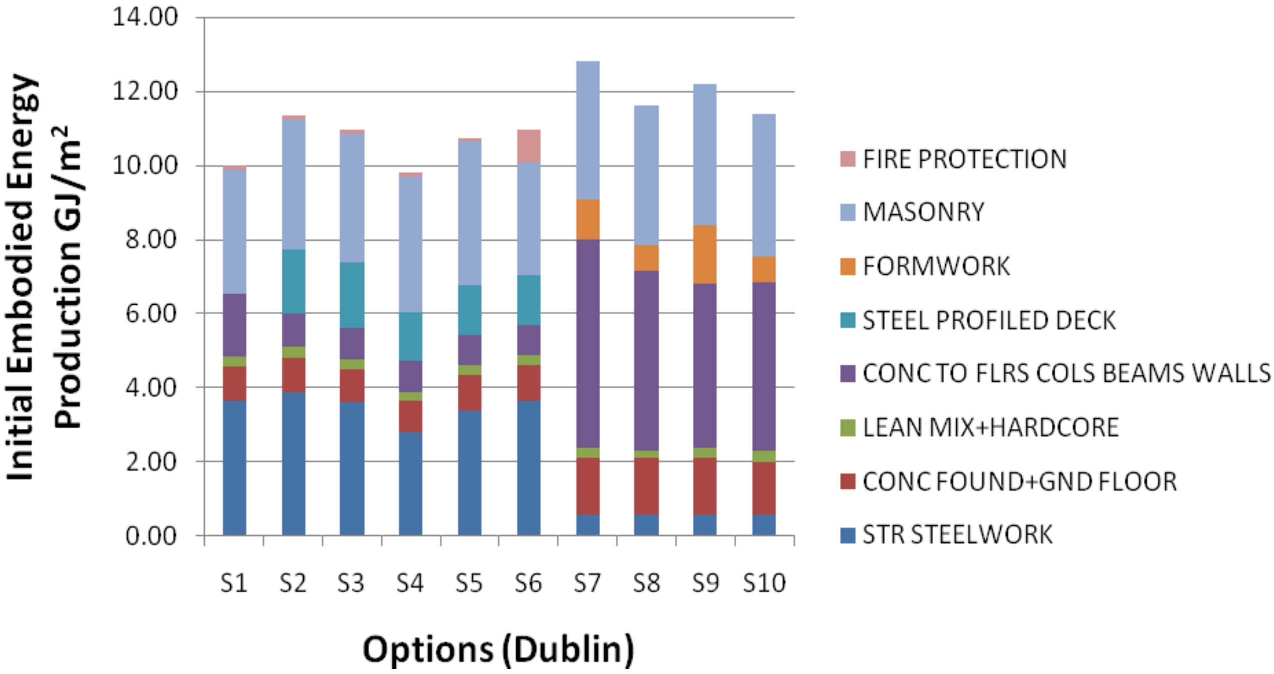

Figure 4.2.2.1 Elemental Initial Embodied Energy – Production (Dublin – GJ)

Area = 2,592m^2

ii) Energy due to transportation of the material

The embodied energy due to road transportation of a material in Ireland is given by;

$E_t \quad = \quad d_1 r$

The embodied energy due to the transportation of steel is given by;

$E_t \quad = \quad QAt_iD_i + d_2 r$

Where

d_1 = average distance from material plant to building site (km)

r = energy intensity of road truck transport in Ireland (MJ/km)

Q = quantity of the material/m^2

A = area of the building

t_i = energy intensity of the mode of transportation from country i to Ireland (MJ/kg.km)

D_i = average nautical distance from country i to the port in Dublin (km)

d_2 = average distance from port in Dublin to the building site (km)

The nautical distances used are those from the largest producing steel exporters in the region to Dublin Port. A weighted nautical distance of 1,457.4 km is adopted. The energy consumption of sea transport is taken as $170x10^{-6}$MJ/kg-km (Acquaye, A. Duffy, A. And Basu, B. 2007).

The average energy intensity of road transport is taken as 12.93MJ/km. An average distance of 6.4km is assumed for the road transport of steel to Dublin Port to the site. The steel carrying capacity of a steelwork truck is 20,000kg (A. Mannion, Structural Engineers). The number of trucks required to transport the steel from Dublin Port to site is obtained by dividing the weight of steel in kg by 20,000kg.

An average road distance of 4.0km from source to site is assumed for the transport of ready mix concrete, hardcore and masonry. The capacity of a concrete mixer is 6.0m^3 which is equivalent to 14,400kg of concrete per truck based on a concrete weight of 2,400kg/m^3. The number of trucks required to transport the concrete from Dublin Port to site is obtained by dividing the weight of concrete in kg by 14,400kg.

An average road distance of 70.0km from source to site is assumed for the transport of pre-cast floors, stairs and landings. An embodied energy intensity of 0.00114MJ/kg/km is adopted for pre-cast concrete (Acquaye, A. Duffy, A. And Basu, B. 2007).

Sample calculations for obtaining the initial embodied energy of the structural steelwork, concrete foundations, pre-cast concrete stairs and pre-cast landings in relation to transportation for structural option 6, composite beams with web openings, are set out below. All weights of material are taken from the Bill of Quantities drawn up for this structural option (Tables 4.1.20 to 4.1.23). The total area of the building is 2,592m^2.

a) Steelwork

E_t (transportation of material)	= $QAt_iD_i + d_2r$	
Weight of steelwork	= 136,730kg	
Weight $/m^2$ Q	= 136,730/2,592	= $52.75kg/m^2$
Average energy consumption of sea transport t_i	= $170x10^{-6}$MJ/kg-km.	
Average nautical distance from source to Dublin Port D_i	= 1,457.4km	
Average distance from port to site in Dublin d_2	= 6.4km	
Average energy intensity of road truck transport in Ireland r	= 12.93MJ/km	
Number of trucks required to transport steel from Dublin Port to site	= 136,730/20,000	= 7
Therefore		
E_t (transportation of material)	= $(52.75)x(2\ 592)x(17010^{-6})$ x(1 457.4)+(6.4) x (12.93)x(7)	= 34,480 MJ
		= 34.48 MJ

b) Concrete foundations

E_t (energy due to transportation of material)	= d_1r	
Weight of concrete	= 387,624 kg	
Average distance from concrete plant to site in Dublin d_1	= 4.0 km	
Average energy intensity of road truck transport in Ireland r	= 12.93 MJ/km	
Number of trucks required to transport concrete from plant to site	= 387,624/14,400	= 27.0
E_t (energy due to transportation of material)	= (4.0)x(12.93)x(27.0)	= 1,396.44 MJ
		= 1.40 GJ

c) Pre-cast landings and stairs

E_t (energy due to transportation of material)	=	d_1r		
Weight of pre-cast concrete landings	=	7,603 kg		
Weight of pre-cast concrete stairs	=	19,013 kg		
Average distance from pre-cast plant to site in Dublin d_1	=	70.0 km		
Average embodied energy intensity r	=	0.00114 MJ/kg/km		
Therefore				
E_t (energy due to transportation of material)	=	(70.0) x (7 603 + 19 013) x (0.00114)	=	2,123.96 MJ
			=	2.123 GJ

The embodied energy for the transportation of materials is shown in Table 4.2.2.5

iii) Energy due to construction

The estimated structural cost of the ten building solutions in this study is incorporated in the calculations of embodied energy due to construction. Statistical data on construction from the Department of Trade and Industry, UK is combined with Irish energy production and carbon intensity data obtained from Sustainable Energy Ireland to calculate the embodied energy due to construction (Acquaye, A, Duffy, A, and Basu, B ,2007). This value is equivalent to 1.1GJ/100k euro.

The initial embodied energy for each of the ten options is obtained by multiplying the cost of the structural frame by the value 1.1GJ/100k euro. This information is set out in Table 4.2.2.5

Table 4.2.2.6 shows the total initial embodied energy and ranking for each structural form due to (i) production, (ii) transportation and (iii)construction and the sum of these initial embodied energies per square metre and their corresponding ranking. This data is also set out graphically in Figure 4.2.2.2

Table 4.2.2.5: Initial Embodied Energy for transportation and construction (Dublin – GJ)

STRUCTURAL OPTION	Transportation	Construction
Option 1 Slimflor® beams and pre-cast hollow core slab	100.60 (10th)	7.96 (1st)
Option 2 Slimflor® beams and deep deck floor (un-propped)	57.13 (7th)	9.10 (4th)
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	53.78 (6th)	8.74 (3rd)
Option 4 Composite beams and floor slab	42.80 (3rd)	8.18 (2nd)
Option 5 Cellular beams or castillated beams and composite slab	48.69 (4th)	9.47 (5th)
Option 6 Composite beams with web openings	51.09 (5th)	9.65 (6th)
Option 7 Reinforced concrete flat slab	18.73 (1st)	10.81 (9th)
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	93.48 (9th)	10.63 (8th)
Option 9 Reinforced concrete waffle slab	19.67 (2nd)	10.90 (10th)
Option 10 Pre-cast double T units on reinforced concrete edge beams	73.00 (8th)	10.50 (7th)

Table 4.2.2.6: Total Initial Embodied Energy and Ranking (Dublin - GJ)

STRUCTURAL OPTION	Prod.	Transport.	Const.	Total Initial Embodied Energy/m² Area 2 592m²
Option 1 Slimflor® beams and pre-cast Hollow core slab	9 999.96 (2nd)	100.6 (10th)	7.96 (1st)	3.89 (2nd)
Option 2 Slimflor® beams and deep deck floor (un-propped)	11 342.99 (6th)	57.13 (7th)	9.10 (4th)	4.40 (6th)
Option 3 Slimflor® beams and deep deck Floor (propped 7.5m span)	10 951.01 (4th)	53.78 (6th)	8.74 (3rd)	4.25 (4th)
Option 4 Composite beams and floor slab	9 795.64 (1st)	42.80 (3rd)	8.18 (2nd)	3.80 (1st)
Option 5 Cellular beams or castillated beams and composite slab	10 783.99 (3rd)	48.69 (4th)	9.47 (5th)	4.18 (3rd)
Option 6 Composite beams with web openings	10 984.72 (5th)	51.09 (5th)	9.65 (6th)	4.26 (5th)
Option 7 Reinforced concrete flat slab	12 806.20 (10th)	18.73 (1st)	10.81 (9th)	4.95 (10th)
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	11 628.47 (8th)	93.48 (9th)	10.63 (8th)	4.53 (8th)
Option 9 Reinforced concrete waffle slab	12 192.94 (9th)	19.67 (2nd)	10.90 (10th)	4.71 (9th)
Option 10 Pre-cast double T units on reinforced concrete edge beams	11 387.47 (7th)	73.00 (8th)	10.50 (7th)	4.42 (7th)

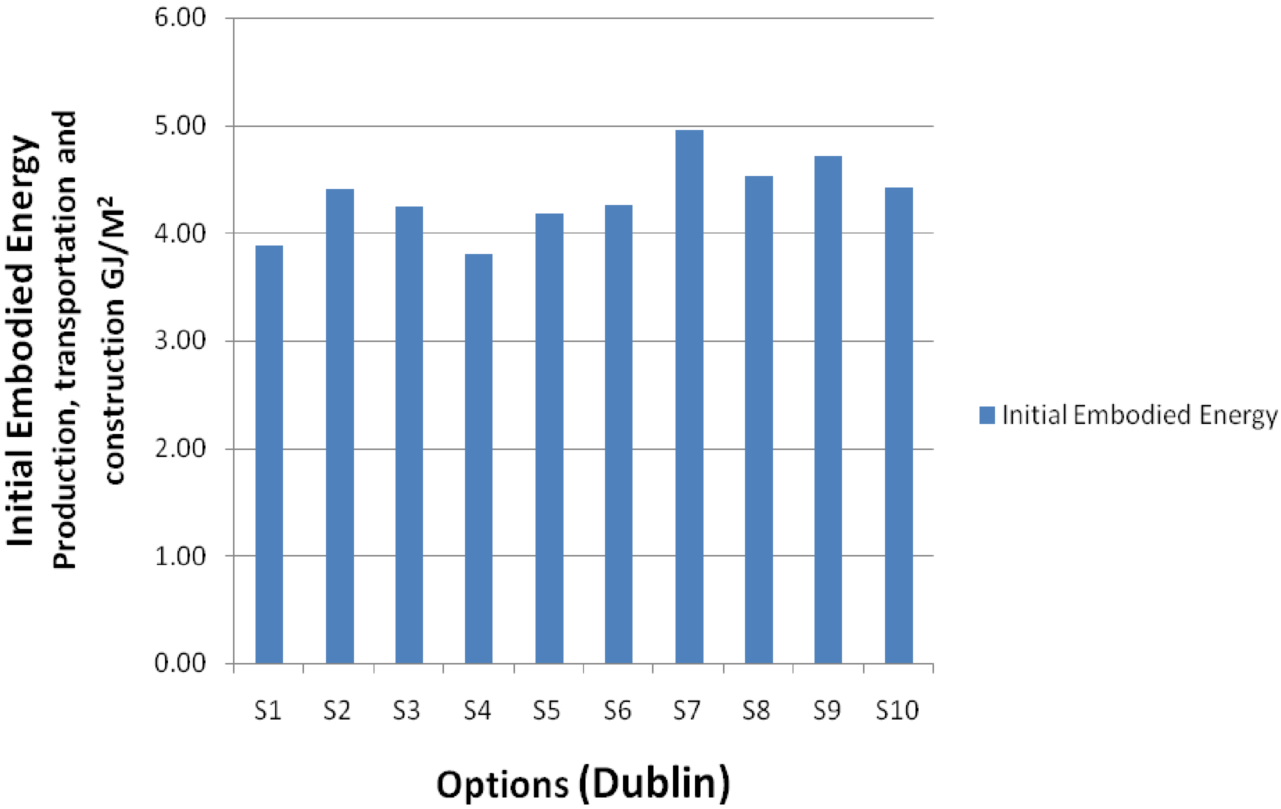

Figure 4.2.2.2 Initial Embodied Energy – Production, Transportation & Construction (Dublin - GJ) Area = 2,592m²

Examination of this data shows that the variation in the total initial embodied energy for the steel options is between 3.8GJ/m^2 for the composite beam and floor slab and 4.4GJ/m^2 for the slimflor® beams and deep deck floor un-propped. This represents a difference of 15.7%. The variation in the total initial embodied energy for the concrete options is between 4.42GJ/m^2 for the pre-cast double T units on reinforced concrete edge beams and 4.95GJ/m^2 for the reinforced concrete flat slab. This represents a difference of 12.0%.

The difference between the options having the lowest and the highest initial embodied energy emissions due to production only is 9,795.64GJ or 3.78GJ/m^2 for option 4 (composite beams and floor slab) and 12,806.20GJ or 4.94GJ/m^2 for option 7 (reinforced concrete slab). This represents a variation of 30.7%.

The major difference amongst the values is in the foundations where the initial embodied energy due to production varies from 863.59GJ to 954.61GJ for the structural steel options and from 1,447.87GJ to 1,547.97GJ for the concrete options. The variation between the lowest and highest value is 80%. Since the volume of concrete used for the pad foundations in the concrete alternatives is twice that used in the steel options, this is not surprising. The percentage difference between volume and the percentage difference between initial embodied energy are not the same as energy intensity values vary depending on the percentage of reinforcement. However, the energy variation between the foundations for the steel and concrete options is reduced when the initial embodied energies for the steel and concrete frames are added.

Steel is used in considerable mass in construction, and there is concern about its relatively high embodied energy emissions compared with those of alternative construction materials (SCI 1994). The production energy intensity coefficient used for the reinforced concrete foundations is between 1.2MJ/kg and 1.5MJ/kg and for concrete beams and columns this value varies between 2.5MJ/kg and 3.5MJ/kg depending on the percentage or weight of reinforcement. For structural steelwork the energy intensity is as high as 25.5MJ/kg. Therefore it would be expected, even without knowing the exact weight of the structural frame, that the values of initial embodied energy for the steel options would be greater than for the concrete forms. This is not always the case. The weight of steel in any building, even if it is steel framed, can be quite low when compared to the total weight of concrete required for foundations, concrete floor infill, lift shafts etc.

The study examines the weight of the various constituents of the steel and concrete frames. The 'frame' includes the make-up of the floor and the vertical members required to support both vertical and lateral loads. Initial embodied energy for production is a function of the mass of the material. The energy intensity value for structural steelwork (25.5MJ/kg) is significantly greater than the value for concrete (1.5 MJ/kg to 3.5MJ/kg). The steel option 1 and the concrete option 7 have approximately the same number of columns and therefore provide a good comparison when considering the initial embodied energy values for the vertical members only.

The weight of the vertical elements, including bracing and shear walls is as follows:

Option 1 25.34Ts

Option 7 394Ts

The initial embodied energy of the vertical elements is given here:

Steelwork	25.5 x 25.34	= 646MJ
Concrete	2.3(average) x 394	= 906MJ

The initial embodied energy for the concrete columns is significantly greater than for the steelwork columns despite the difference between energy intensity values. This indicates that if initial embodied energy is to be regarded as a serious criterion in the selection of a structural form, major consideration should be given to the column material Weight is a critical element in the derivation of initial embodied energy.

In order to explain this further, the study makes a comparison between two of the selected building forms where both use precast hollow floors on a structural frame. It looks at the weight of the frame i.e. beams, columns and bracing elements only, for the steel option 1 (slimflor® beams and pre-cast hollow core slab) and for the concrete option 8 (pre-cast hollow core units on reinforced concrete edge beams). The weight of a material is required to find its initial embodied energy. The weight of the steelwork frame is 136,790kg and the weight of the concrete frame, which is taken as 2,400kg/m^3, is 775,704kg. The weight of the concrete is considerably greater than the weight of the steel frame. However, a simple calculation will show that in terms of initial embodied energy for material production, excluding material waste, the initial embodied energy for the concrete frame is now less than that for the steel frame.

Steel energy intensity coefficient e_i	= 25.50 MJ/kg	
E_p (energy due to production of material)	= (25.5)x(136 790)	= 3,488,145 MJ
		= 3,488,145/2,592 MJ/m^2
		= 1,345.73 MJ/m^2
		= 1.35 GJ/m^2
Average reinforced concrete energy intensity coefficient e_i	= 3.0 MJ/kg	
E_p (energy due to production of material)	= (3.0)x(775,704)	= 2,327,112.0 MJ
		= 2,327 112.0 /2,592 MJ/m^2
		= 897.80 MJ/m^2
		= 0.90 GJ/m^2

The weight of the concrete frame is nearly six times greater than the weight of the steel frame and yet the initial embodied energy for the steel frame is 50% greater than the concrete frame. The gap between the two structural forms is quickly reversed once the initial embodied energy values for the foundations, formwork to beams, columns and shear walls are added. It should also be noted that the upper floors to the concrete and steel options are 400mm deep and 200mm deep respectively. The floor to the concrete option could be reduced to 200mm if more columns and beams were introduced. It would be interesting to see if it made any difference to the initial embodied energy.

Production of the material accounts for most of the initial embodied energies. The energy used for the transportation of structural steelwork for the steel options is more than twice that required for the transportation of the materials used in the concrete options. This is obviously due to the fact that steel is transported from steel producing countries all over the world, while concrete is transported from plants locally. This variation contributes very little to the overall values of initial embodied energy.

The energy used in construction is a reflection of the cost of the building but is quite insignificant when considering the total values of initial embodied energy.

The data shows that the structural options found to have the least initial embodied energy per square metre (total area is 2,592m^2) are:

Option 4 3.80GJ/m^2 (Composite beams and composite floor slab)

Option 1 3.89GJ/m^2 (Slimflor® beams and pre-cast hollow core slab)

The structural forms found to have the most initial embodied energy are:

Option 7 4.95GJ/m^2 (Reinforced concrete flat slab)

Option 9 4.71GJ/m^2 (Reinforced concrete waffle slab)

It is clear that the choice of structural option can have an impact on the emissions of initial embodied energy and that the quantity of structural steelwork is a major consideration. The choice of material therefore plays an important role in helping countries meet their international emissions commitments.

4.3 Frame Construction Time

The erection of the main structural frame ranges from 6 to 7 weeks for the steelwork options and 9 to 12 weeks for the concrete options. The increased construction time between the steelwork forms is due to propping and the installation of the shear studs. The increased construction time in the in-situ concrete options is due to fixing of reinforcement, curing of concrete, striking of formwork and propping during construction. Also, an additional 2 weeks is required for the construction of the ground bearing floor slab for the concrete options before commencement of the concrete frame.

The erection of the steelwork columns is done in lifts of two floors at a time whereas the in-situ concrete columns are poured one floor at a time to allow fixing of reinforcement at the intersection between concrete floors and beams. This adds to the frame construction time.

These considerations have been taken into account within the main contractor's preliminaries for time related preliminaries on those structural options where the contract periods are likely to be longer.

Table 4.3.1 summarises the frame construction time for each of the ten options.

The ranking of the 10 options on the basis of frame construction time are:

1st	**Option 2**	(Slimflor® beams and deep deck floor un-propped)
2nd	**Option 1**	(Slimflor® beams and pre-cast hollow core slab)
	Option 3	(Slimflor® beams and deep deck floor propped)
	Option 4	(Composite beams and composite floor slab)
	Option 5	(Cellular beams or castellated beams and composite slab)
	Option 6	(Composite beams with web openings)
7th	**Option 8**	(Pre-cast hollow core units on R.C. edge beams)
	Option 10	(Precast double T units on reinforced concrete edge beams)
9th	**Option 7**	(Reinforced concrete flat slab)
10th	**Option 9**	(Reinforced concrete waffle slab)

Table 4.3.1: Summary of frame construction time (Dublin)

STRUCTURAL OPTION	Frame Construction Time (weeks)
Option 1 Slimflor® beams and pre-cast hollow core slab	7 (2nd)
Option 2 Slimflor® beams and deep deck floor (un-propped)	6 (1st)
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	7 (2nd)
Option 4 Composite beams & composite floor slab	7 (2nd)
Option 5 Cellular beams or castillated beams and composite floor slab	7 (2nd)
Option 6 Composite beams with web openings	7 (2nd)
Option 7 Reinforced concrete flat slab	10 (9th)
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	9 (7th)
Option 9 Reinforced concrete waffle slab	12 (10th)
Option 10 Pre-cast double T units on reinforced concrete edge beams	9 (7th)

4.4 Overall Construction Time

Speed of construction and tight construction programmes are primary considerations in most building contracts

Global demand for steel is growing at about 10% a year, and remains a popular choice because of its speed and ease of erection. It is especially popular for offices. Concrete remains the material of choice for the residential sector due to its sound and fire-proofing qualities. Concrete's excellent thermal mass is also being considered by more and more designers as a way of significantly reducing the amount of energy used in buildings (Building-Specialist cost update: Structures, 2007).

The average lead-in time (time for checking and approving workshop drawings, ordering, procurement etc.) for in-situ concrete frames has remained reasonably static at five weeks. The primary factor in determining this lead-in time remains the procurement of steel reinforcement. This also adds to the construction time of the concrete columns. Steelwork columns can be erected as soon as they arrive on site and are not dependent on the other trades required for in-situ concretes such as fixing of steel reinforcement, cutting and striking of formwork, installation of fire boarding and curing. Trade contractors have reported that they can mobilise and be on site in three to four weeks, but the detailing of reinforcement and issuing of bar bending schedules by engineers tend to lag behind this timescale. These are usually required 10 to 15 days before the steel is needed on site to avoid the cost of express ordering. The lead-in time for pre-cast hollow core slabs tends to be 2 weeks on average for the size of structure discussed in this study. This time includes working drawings, approval of drawings and manufacture.

With regard to lead-in times for steelwork, the large contractors are now involved for several weeks finalising design and value of engineering schemes prior to the commencement of working drawings. Steel construction lead-in time figures of 10 to 12 weeks are fairly typical for the structure analysed here (A.Mannion Structural Engineers). The information that engineers and contractors really need to know is the elapsed time from placing an order to the time of start of delivery of steelwork to site and the commencement of erection. This varies depending upon the size and complexity of the project. For relatively straightforward projects, the period from receipt of order with full information to start of delivery is typically 9 to 11 weeks which are built up as follows:

- Working drawings 4 weeks
- Approve drawings 4 weeks
- Manufacture 3 weeks

However, with no early involvement of contractors the lead-in times can be 12 to 14 weeks.

The breakdown of the various activities within the overall construction programme is presented in Figure 4.4.1 for option 2, slimflor® beams and deep deck floor (un-propped). This is a representative example and was carried out for all options in order to assess the frame and overall construction times.

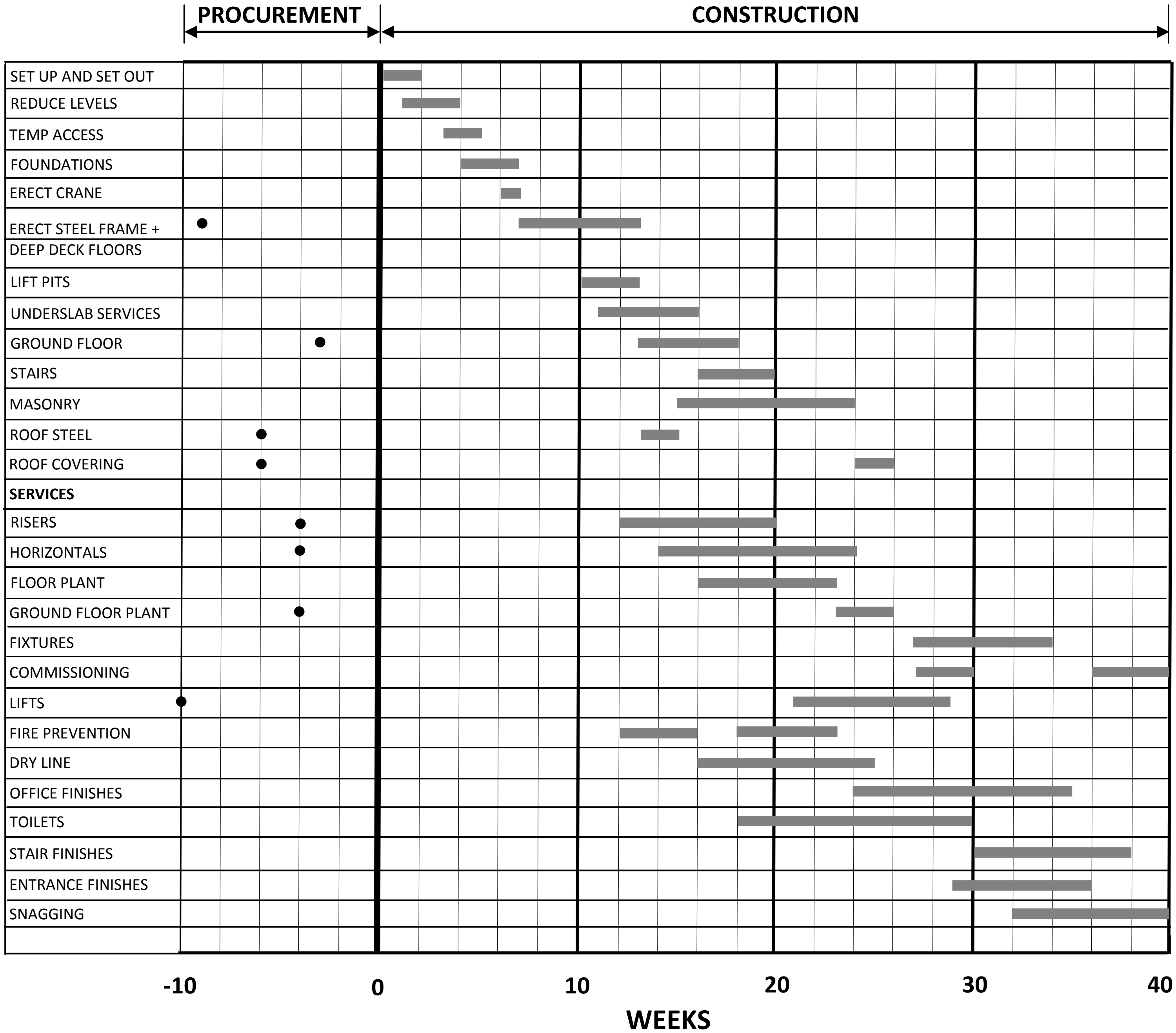

Figure 4.4.1: Construction programme for option 2 (Dublin) Slimflor® beams and deep deck floor (un-propped)

Table 4.4.2 summarises the overall construction time of each of the ten options. The programme includes the order time for the steelwork, pre-cast hollow core slabs and stairs, lifts and services. While the study does not address such items as plant, services, fittings, lift installation and finishes in relation to cost and initial embodied energy it was necessary to include them in the overall programme in order to give a true representation of the construction period. This information is provided by Cormac Construction, Dublin and shown graphically in Figure 4.4.2

Table 4.4.2: Summary of overall construction time (Dublin)

STRUCTURAL OPTION	Overall Construction Time (weeks)
Option 1 Slimflor® beams and pre-cast hollow core slab	41 (2nd)
Option 2 Slimflor® beams and deep deck floor (un-propped)	40 (1st)
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	42 (4th)
Option 4 Composite beams & composite floor slab	41 (2nd)
Option 5 Cellular beams or castillated beams and composite floor slab	42 (4th)
Option 6 Composite beams with web openings	42 (4th)
Option 7 Reinforced concrete flat slab	46 (9th)
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	44 (8th)
Option 9 Reinforced concrete waffle slab	48 (10th)
Option 10 Pre-cast double T units on reinforced concrete edge beams	43 (7th)

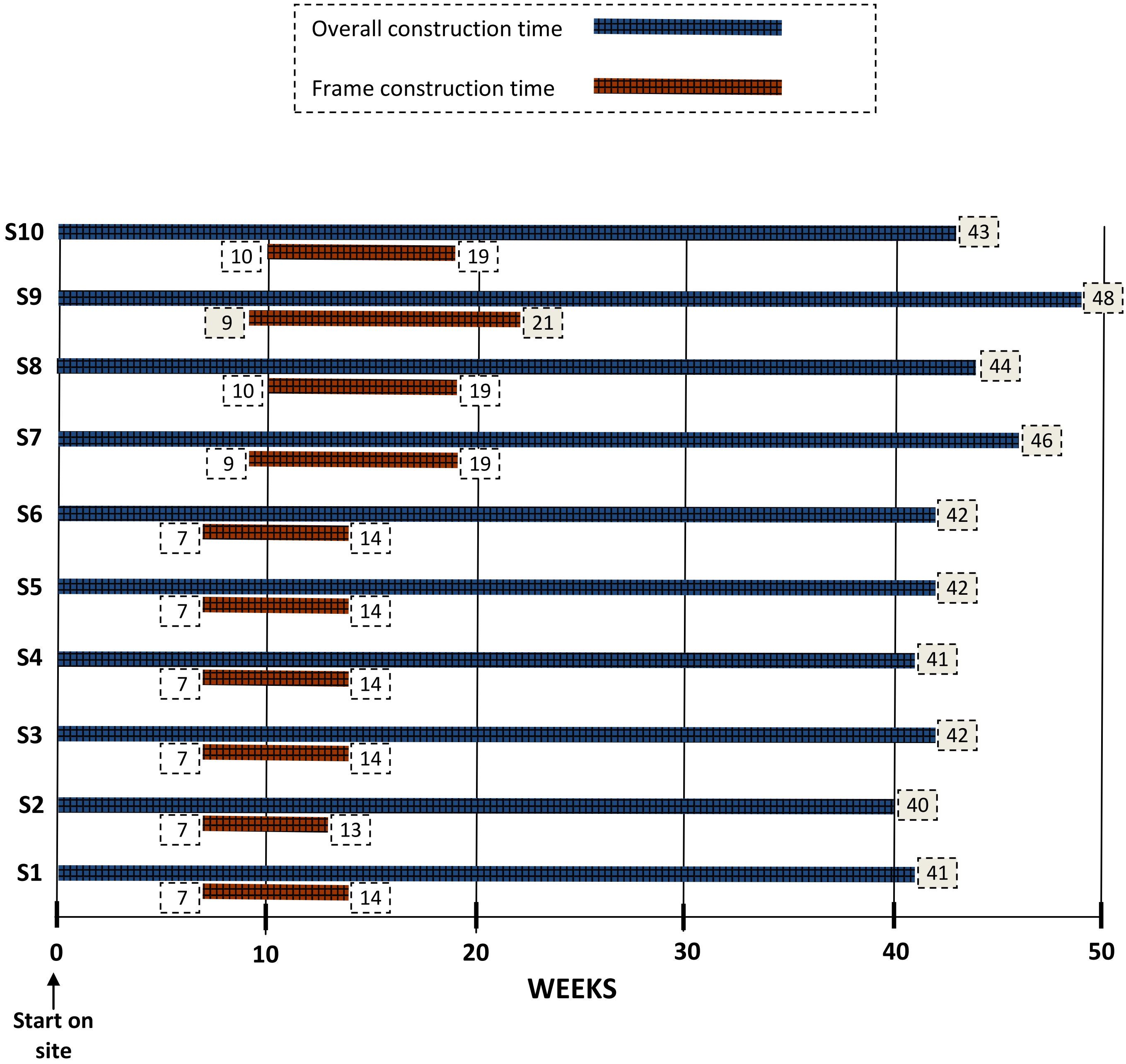

Figure 4.4.2: Frame and overall construction time (Dublin)

The ranking of the 10 options on the basis of overall construction are:

1st	**Option 2**	(Slimflor® beams and deep deck floor un-propped)
2nd	**Option 1**	(Slimflor® beams and pre-cast hollow core slab)
	Option 4	(Composite beams and composite floor slab)
4th	**Option 3**	(Slimflor® beams and deep deck floor propped)
	Option 5	(Cellular beams or castellated beams and composite slab)
	Option 6	(Composite beams with web openings)
7th	**Option 10**	(Precast double T units on reinforced concrete edge beams)
8th	**Option 8**	(Pre-cast hollow core units on R.C. edge beams)
9th	**Option 7**	(Reinforced concrete flat slab)
10th	**Option 9**	(Reinforced concrete waffle slab)

5 Comparison of the various Options between the Irish and British construction industries in relation to cost and initial embodied energy

5.1 Comparison of cost

This part of the study examines and compares the differences in cost between the building analysed in this study and the similar building in Manchester analysed in the SCI publication, 2004. The study is carried out with regard to the total elemental costs and the costs per square metre of gross floor area for the variable elements of each of the 10 structural options. It is not the purpose of this study to compare British and Irish construction costs. Its function is to look at the price differences between steelwork and concrete options for each location separately and conclude if there are similarities.

The methodology involved in compiling this data is to:

- Obtain from the SCI publication, 2004, the cost /m^2 of the variable items and the ground floor slab for each of the ten options. The variable items include sub-structure, upper floors and frame, stairs and external walls (masonry)
- Add on the preliminaries and contingencies as applied in the SCI publication, 2004
- Tabulate the information so that it can be compared to the results obtained within this study for the building in Dublin.
- Produce a bar chart showing the basic cost and overall cost of the ten structural alternatives

The aim of this section is to:

- Compare the basic cost and overall costs of the ten structural forms in Dublin and Manchester.
- Determine the cheapest and most expensive structural frame in both locations
- Determine if there is any significant difference between the cost of the steel and composite structures and the concrete frames in both locations

Tables 5.1.1 and 5.1.2 indicate the total elemental costs and the costs per square metre of gross floor area for each of the structural options for the building in Manchester SCI (1994). This data is also presented graphically in Figure 5.1.1 Main contractors' preliminaries and contingencies have been added. The preliminaries vary from 12.9% to 13.7% of the basic cost and are much higher than in Dublin where they range from 6.3% to 7.8%. This is most likely due to the very competitive market of 2008 when development and land prices were at their highest (Cormac Construction). Contingencies are added to the basic cost plus preliminaries at a rate of 7.5% and are similar to the values applied in Dublin.

Table 5.1.1: Elemental Costs /m^2 (Outer Manchester - £/m^2) (Total Area 2,592m^2)

STRUCTURAL OPTION	Sub Structure	Upper Floor Roof & Frame	Stairs	External Walls	Sub Total
Option 1 Slimflor® beams and pre-cast hollow core slab	27.00	85.00	18.00	65.00	**195.00 (2nd)**
Option 2 Slimflor® beams and deep deck floor (un-propped)	26.00	91.00	18.00	67.00	**202.00 (4th)**
Option 3 Slimflor® beams and deep deck Floor (propped 7.5m span)	26.00	90.00	18.00	67.00	**201.00 (3rd)**
Option 4 Composite beams and floor slab	25.00	71.00	19.00	70.00	**185.00 (1st)**
Option 5 Cellular beams or castillated beams and composite slab	26.00	91.00	20.00	77.00	**213.00 (5th)**
Option 6 Composite beams with web openings	26.00	97.00	19.00	76.00	**218.00 (6th)**
Option 7 Reinforced concrete flat slab	37.00	118.00	18.00	67.00	**240.00 (10th)**
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	34.00	101.00	19.00	72.00	**226.00 (7th)**
Option 9 Reinforced concrete waffle slab	37.00	114.00	19.00	69.00	**239.00 (9th)**
Option 10 Pre-cast double T units on reinforced concrete edge beams	34.00	99.00	19.00	75.00	**227.00 (8th)**

Table 5.1.2: Elemental Costs /m² (Manchester - £/m²) (Total Area 2,592m²)

STRUCTURAL OPTION	Preliminaries (12.9%-13.7%)	Sub Total	Contingency (7.5%)	Total Cost Per sq. metre
Option 1 Slimflor® beams and pre-cast hollow core slab	25.35 (13.0%)	**220.35**	16.52	**236.87 (2nd)**
Option 2 Slimflor® beams and deep deck floor (un-propped)	26.05 (12.9%)	**228.05**	17.10	**245.15 (4th)**
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	26.00 (12.9%)	**227.00**	17.03	**244.03 (3rd)**
Option 4 Composite beams and floor slab	25.34 (13.7%)	**210.34**	15.78	**226.12 (1st)**
Option 5 Cellular beams or castillated beams and composite slab	27.48 (12.9%)	**240.48**	18.04	**258.52 (5th)**
Option 6 Composite beams with web openings	28.12 (12.9%)	**246.12**	18.46	**264.58 (6th)**
Option 7 Reinforced concrete flat slab	31.92 (13.3%)	**271.92**	20.40	**292.32 (10th)**
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	30.05 (13.3%)	**256.05**	19.20	**275.25 (7th)**
Option 9 Reinforced concrete waffle slab	31.79 (13.3%)	**270.79**	20.31	**291.10 (9th)**
Option 10 Pre-cast double T units on reinforced concrete edge beams	30.19 (13.3%)	**257.19**	19.29	**276.48 (8th)**

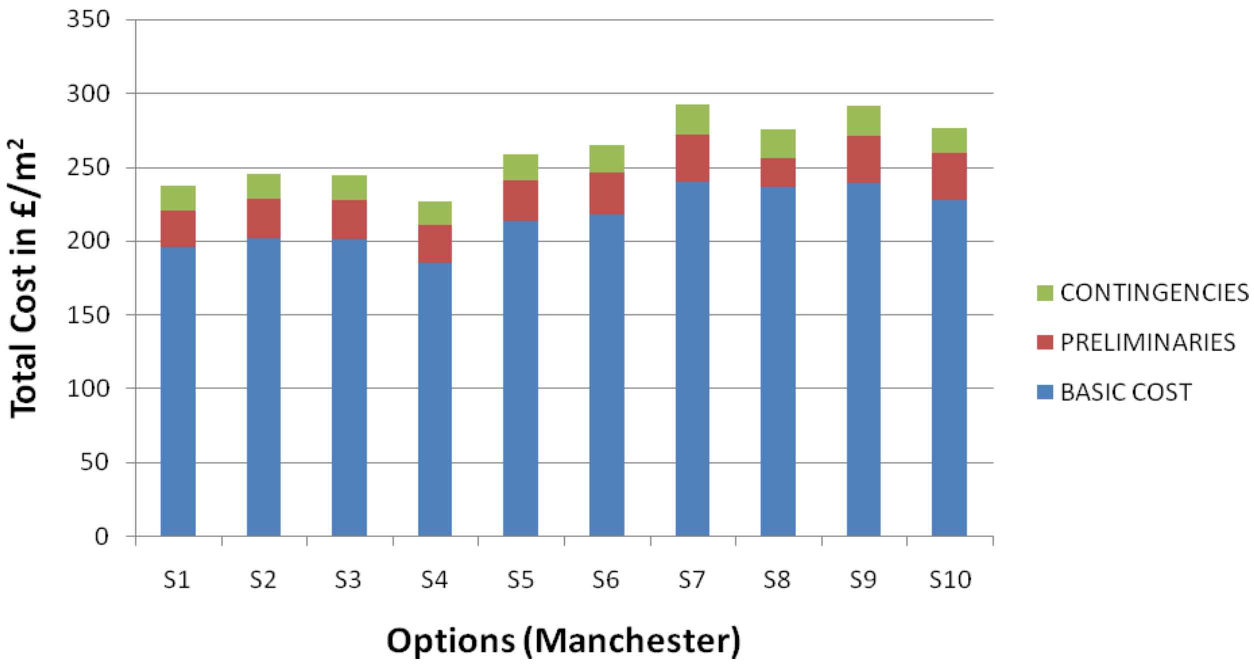

Figure 5.1.1 Total elemental costs /m^2 - Manchester (Area = 2,592m^2)

Table 5.1.3 shows the price list ranking of each of the options in Dublin and Manchester. The values shown are with and without main contractors' preliminaries and contingencies.

Table 5.1.3: Price list ranking/m^2 of each option in Dublin and Manchester

STRUCTURAL OPTION (Ranking in terms of cost/m^2)	Manchester (£/m^2)	Dublin (euro/m^2)	Manchester (Inc. Prelims & Contingencies) (£/m^2)	Dublin (Inc. Prelims & Contingencies) (euro/m^2)
Option 1 Slimflor® beams and pre-cast hollowcore slab	195.00 (2nd)	279.35 (1st)	236.87 (2nd)	319.82 (1st)
Option 2 Slimflor® beams and deep deck floor (un-propped)	202.00 (4th)	319.13 (4th)	245.15 (4th)	364.67 (4th)
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	201.00 (3rd)	306.63 (3rd)	244.03 (3rd)	351.05 (3rd)
Option 4 Composite beams and floor slab	185.00 (1st)	287.21 (2nd)	226.12 (1st)	329.13 (2nd)
Option 5 Cellular beams or castillated beams and composite slab	213.00 (5th)	332.31 (5th)	258.52 (5th)	380.11 (5th)
Option 6 Composite beams with web openings	218.00 (6th)	338.60 (6th)	264.58 (6th)	387.29 (6th)
Option 7 Reinforced concrete flat slab	240.00 (10th)	379.30 (9th)	292.32 (10th)	438.74 (9th)
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	226.00 (7th)	373 32 (8th)	275.25 (7th)	431.42 (8th)
Option 9 Reinforced concrete waffle slab	239.00 (9th)	382.55 (10th)	291.10 (9th)	443.30 (10th)
Option 10 Pre-cast double T units on reinforced concrete edge beams	227.00 (8th)	367.42 (7th)	276.48 (8th)	424.60 (7th)

In Manchester, the ranking of the 10 options per square metre on the basis of cost including preliminaries and contingencies is:

1st	**Option 4**	**£226.12**	(Composite beams and composite floor slab)
2nd	**Option 1**	**£236.87**	(Slimflor℗ beams and pre-cast hollow core slab)
3rd	**Option 3**	**£244.03**	(Slimflor℗ beams and deep deck floor propped)
4th	**Option 2**	**£245.15**	(Slimflor℗ beams and deep deck floor un-propped)
5th	**Option 5**	**£258.52**	(Cellular beams/castellated beams and composite slab)
6th	**Option 6**	**£264.58**	(Composite beams with web openings)
7th	**Option 8**	**£275.25**	(Pre-cast hollow core units on R.C. edge beams)
8th	**Option 10**	**£276.48**	(Precast double T units on reinf'd conc edge beams)
9th	**Option 9**	**£291.10**	(Reinforced concrete waffle slab)
10th	**Option 7**	**£292.32**	(Reinforced concrete flat slab)

Examination of the above results will show that the variation between the options is not as great as in Dublin. All steel options are cheaper than the concrete alternatives with a difference of 21.7% between the least expensive steel form and the least expensive concrete option compared to 32.7% in Dublin. This represents a structural cost difference of £49.13 per square metre or £127,344 in total. The variation between the least expensive and most expensive structural form is 29.3% compared to 38.6% in Dublin. This is equivalent to a structural cost difference of £66.2 per square metre or £171,590.4 in total.

The cost difference between the least expensive and most expensive steel options is 17% and between the least expensive and most expensive concrete forms is 6.2%. In Dublin the corresponding figures are 21.0% and 4.4%.

The application of preliminaries between 12.9% and 13.7% to the basic cost does not change the ranking of the structural alternatives. It is also the same situation in Dublin.

The only difference in the ranking of the steel alternatives in Manchester applies to option 1 (composite beams and composite floor slab) and option 4 (slimflor℗ beams and deep deck floor un-propped). In Dublin, option 1 is the cheapest structural form while in Manchester it is the second cheapest. Option 4 is the least expensive structure in Manchester but is only the second cheapest in Dublin. This accounts for a difference of 2.9% in Dublin and 4.75% in Manchester. All other steel forms are ranked similarly in Dublin and Manchester.

The structural cost rankings of the concrete alternatives are not the same for Dublin and Manchester. Option 10 (precast double T units on reinforced concrete edge beams) and option 8 (Pre-cast hollow core units on R.C. edge beams) rank 7th and 8th respectively and in Manchester these options are ranked 8th and 7th respectively. This accounts for a difference of 1.6% in Dublin and 0.45% in Manchester. Option 7 (reinforced concrete flat slab) and option 9 (reinforced concrete waffle slab) rank 9th and 10th respectively and in Manchester these options are ranked 10th and 9th respectively. This accounts for a price variation of 1.03% in Dublin and 0.42% in Manchester.

The most significant difference between the two locations is the variation in the cost of the substructure. In Manchester this varies (excluding preliminaries and contingencies) from £25.0/m2 or £64,800 in total to 27£/m2 or £69,984 in total for the steel alternatives and £34.0/m2 or £88,128 in total to £37.0/m2 or £95,904 in total for the concrete forms. The increase in substructure cost between the most expensive steel option and the least expensive concrete option is 25.9% and 48.0% between the least and most expensive options. In Dublin the equivalent variation in the cost of the substructure varies from 68,826.15 euro to 73,603.45 euro in total and from 99,720.80 euro to 106,555.80 euro in total. The increase cost between the most expensive steel option and the least expensive concrete option is 35.40% and 54.8% between the least and most expensive options.

5.2 Comparison of Initial Embodied Energy

In 1994 the Steel Construction Institute produced a publication 'A Comparative Environmental Life Cycle Assessment of Modern Office Buildings' which compares the initial embodied energy of the same structural forms analysed for cost, frame construction time and overall construction time in the SCI publication (2004). It was initiated by British Steel and the Department of the Environment, Transport and the Regions in 1994. The study focuses on initial embodied energy and embodied CO_2 emission values.

The SCI publication, 1994 analysed the initial embodied energy for production for each construction alternative using information from the comprehensive database for construction materials available at Davis Langdon Consultancy. The publication addressed the initial embodied energy in two sections:

1. Foundations and all sub-structure, superstructure, including all staircases, lift shafts and external walls
2. Windows and external doors, internal walls, partitions and doors, wall finishes, floor finishes, ceiling finishes, fittings, sanitary fittings and disposal, mechanical and electrical services, lift installation, construction and transportation.

This study compares the results obtained for Dublin and those assessed for Manchester in 1 above of the SCI publication, 1994. The results from the publication do not include a breakdown of the individual materials or the material embodied energy (*mee*) coefficients for production assigned to each material. However, it is possible to make a comparison of the sum of the initial embodied energy for production of the items in 1 above for each of the ten structural forms in both Dublin and Manchester.

The methodology involved in compiling the data is to:

- Obtain from the SCI publication, 1994, the initial embodied energy, due to production, for the ten structural alternatives in Manchester.
- Tabulate the information so that it can be compared to the results obtained within this study for the building in Dublin.
- Produce a bar chart representing the data for each of the frame options

The aim of this section is to:

- Compare the initial embodied energy for production only of the ten structural forms in Dublin and Manchester.
- Determine the which of the ten structural forms produces the most and least initial embodied energy in both locations
- Determine if there is any significant difference between the initial embodied energy for the steel and composite structures and the concrete frames in both locations

Table 5.2.1 gives the total initial embodied energy per square metre (SCI 1994) relative to production only for the 10 structural frames in Manchester and the equivalent values for Dublin. The information relating to Manchester is presented graphically in Figure 5.2.1

Table 5.2.1: Initial embodied energy due to production (Dublin & Manchester- GJ/m²) (Total Area 2,592m²)

STRUCTURAL OPTION	Dublin	Manchester
Option 1 **Slimflor® beams and pre-cast hollow core slab**	**3.86 (2nd)**	**2.63 (3rd)**
Option 2 **Slimflor® beams and deep deck floor (un-propped)**	**4.38 (6th)**	**2.75 (6th)**
Option 3 **Slimflor® beams and deep deck floor (propped 7.5m span)**	**4.22 (4th)**	**2.65 (4th)**
Option 4 **Composite beams and floor slab**	**3.78 (1st)**	**2.70 (5th)**
Option 5 **Cellular beams or castillated beams and composite slab**	**4.16 (3rd)**	**2.98 (9th)**
Option 6 **Composite beams with web openings**	**4.24 (5th)**	**3.12 (10th)**
Option 7 **Reinforced concrete flat slab**	**4.94 (10th)**	**2.50 (2nd)**
Option 8 **Pre-cast hollow core units on reinforced concrete edge beams**	**4.49 (8th)**	**2.80 (7th)**
Option 9 **Reinforced conc. waffle slab**	**4.70 (9th)**	**2.48 (1st)**
Option 10 **Pre-cast double T units on Reinforced concrete edge beams**	**4.39 (7th)**	**2.80 (7th)**

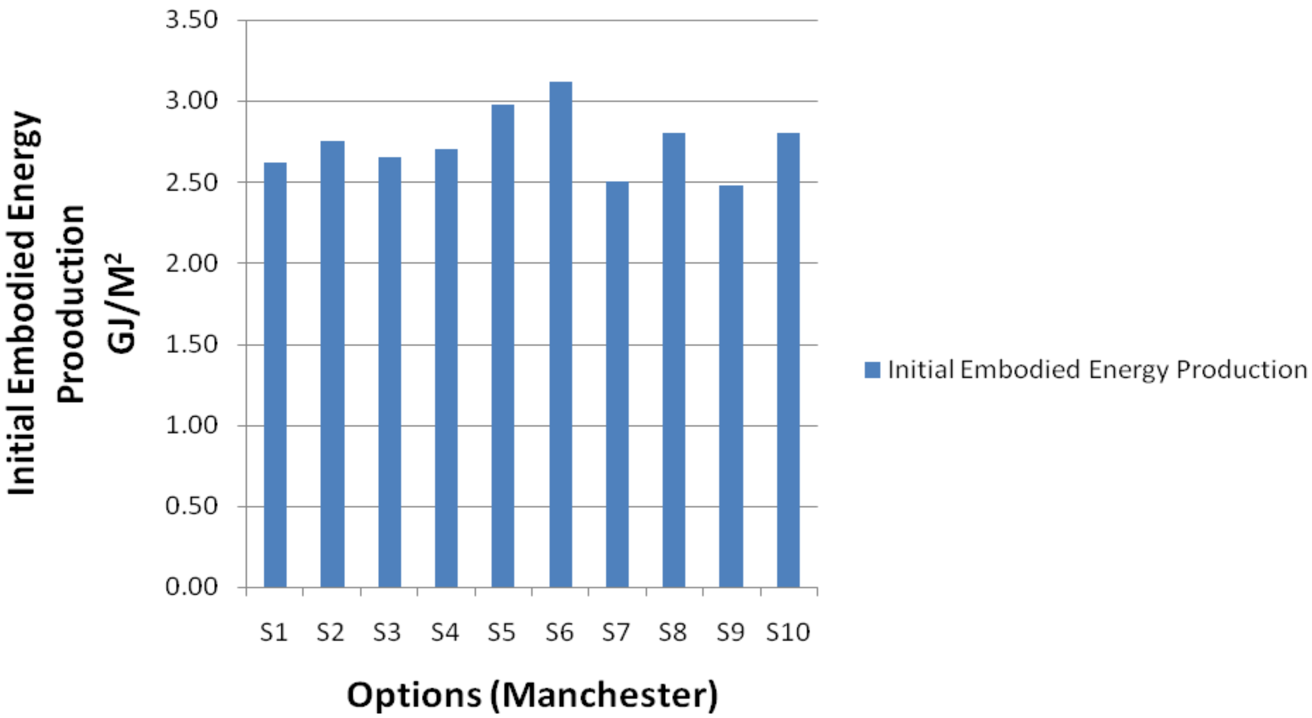

Figure 5.2.1 Initial Embodied Energy – Production (Manchester)

Area = 2,592m^2

Within the Irish industry the variation between the values of initial embodied energy across the range of steelwork construction options for production is 3.78GJ/m^2 for the composite beam and floor slab and 4.38GJ/m^2 for the Slimflor® beams and deep deck floor (un-propped). This represents a difference of 15.9%. The variation between the concrete alternatives is 12.5% where the initial embodied energy is 4.39GJ/m^2 for the double T units on reinforced concrete edge beams and 4.94GJ/m^2 for the reinforced concrete flat slab. The variation between the lowest value for the composite beam and floor slab and the highest value for the reinforced concrete flat slab is 30.7%. The initial embodied energy for the six steel structural forms is less than the values for the four concrete forms.

In Manchester the variation across the range of steelwork options is 2.63GJ/m^2 for the slimflor® beams and pre-cast hollow core slab and 3.12GJ/m^2 for the composite beams with web openings. This represents a variation of 18.63% compared to 15.9% for Dublin. The variation between the concrete alternatives is 2.48GJ/m^2 for the reinforced concrete waffle slab and 2.80GJ/m^2 for the pre-cast double T units on reinforced concrete edge beams and the pre-cast hollow core units on reinforced concrete edge beams. This represents a difference of 12.9% compared to 12.5% for Dublin. The variation between the lowest value for the reinforced concrete waffle slab and the highest value for the composite beams with web openings is 25.8%.

The ranking of the options in Dublin does not change when the initial embodied energy due to transportation and construction is added. The initial embodied energy for transportation and construction is found to be very small when compared to the values for production. This study, for the purpose of the multi criteria decision analysis, will assume that the same applies to the ranking for Manchester. The SCI publication does not give separate information for these two activities.

In Manchester the initial embodied energy is not less for the six steel structural forms. In contrast to the values for Dublin, two of the concrete forms, the reinforced concrete waffle slab and the reinforced concrete flat slab, have less initial embodied energy than any of the steel alternatives. The steel option 6, composite beam with web openings, has the highest value. Since the SCI publication, 1994, does not give a breakdown of the material embodied energy (*mee*) coefficients for production assigned to each material, it is difficult to determine where exactly the values for Dublin and Manchester differ.

The information for the SCI publication was gathered in 1994 from the comprehensive database for construction materials available at Davis Langdon Consultancy and the data for this study was obtained from the Inventory of Carbon and Energy (ICE), 2006. The increased interest in sustainability and how it may affect the future has required a number of studies, including the ICE publication, 2006, to be carried out (SCI, 2003). It is possible that values of initial embodied energy have been further investigated and refined.

5.3 Frame construction time

Table 5.3.1 shows the frame construction time construction time for each of the structural forms in Manchester as produced by MACE Limited (England) (SCI 2004). This study does not include a comparative discussion of the frame construction time in Dublin and Manchester. The information is required only for the Multi Criteria Decision Analysis.

The methodology involved in compiling the data is to:

- Obtain from the SCI publication, 2004, the frame construction time for the ten structural alternatives in Manchester.
- Tabulate the information.

The aim of this section is to:

- Compile the frame construction times for each of the ten structural alternatives so that they may be used for the Multi Criteria Decision Analysis

Table 5.3.1: Frame construction time (Manchester)

STRUCTURAL OPTION	Frame Construction Time (weeks)
Option 1 Slimflor® beams and pre-cast hollow core slab	7 (4th)
Option 2 Slimflor® beams and deep deck floor (un-propped)	6 (1st)
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	7 (4th)
Option 4 Composite beams and composite floor slab	7 (4th)
Option 5 Cellular beams or castillated beams and composite floor slab	6 (1st)
Option 6 Composite beams with web openings	6 (1st)
Option 7 Reinforced concrete flat slab	8 (7th)
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	8 (7th)
Option 9 Reinforced concrete waffle slab	13 (10th)
Option 10 Pre-cast double T units on reinforced concrete edge beams	8 (7th)

5.4 Overall construction time

Table 5.4.1 shows the overall construction time for each of the structural forms in Manchester as produced by MACE Limited (England) (SCI 2004). This study does not include a comparative discussion of the overall construction time in Dublin and Manchester. The information is required only for the Multi Criteria Decision Analysis.

The methodology involved in compiling the data is to:

- Obtain from the SCI publication, 2004, the overall construction time for the ten structural alternatives in Manchester.
- Tabulate the information.

The aim of this section is to:

- Compile the overall construction times for each of the ten structural alternatives so that they may be used for the Multi Criteria Decision Analysis.

Table 5.4.1: Overall construction time (Manchester)

STRUCTURAL OPTION	Overall Construction Time (weeks)
Option 1 Slimflor® beams and pre-cast hollow core slab	42 (4th)
Option 2 Slimflor® beams and deep deck floor (un-propped)	40 (1st)
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	42 (4th)
Option 4 Composite beams and composite floor slab	42 (4th)
Option 5 Cellular beams or castillated beams and composite floor slab	41 (2nd)
Option 6 Composite beams with web openings	41 (2nd)
Option 7 Reinforced concrete flat slab	43 (7th)
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	43 (7th)
Option 9 Reinforced concrete waffle slab	50 (10th)
Option 10 Pre-cast double T units on reinforced concrete edge beams	43 (7th)

5.5 Summary of ranking of options in Dublin and Manchester

The rankings of the ten options on each of the four criteria – cost, initial embodied energy, frame construction time and overall construction time – for Dublin and Manchester are presented in Tables 5.5.1 and 5.5.2.

Table 5.5.1: Summary of ranking of options on criteria C1 & C2 in Dublin and Manchester

Structural Option	Cost C1		Initial Embodied Energy C2	
	Dublin	Manchester	Dublin	Manchester
Option 1 Slimflor® beams and pre-cast hollowcore slab	1st	2nd	2nd	3rd
Option 2 Slimflor® beams and deep deck floor (un-propped)	4th	4th	6th	6th
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	3rd	3rd	4th	4th
Option 4 Composite beams and floor slab	2nd	1st	1st	5th
Option 5 Cellular beams or castillated beams and composite slab	5th	5th	3rd	9th
Option 6 Composite beams with web openings	6th	6th	5th	10th
Option 7 Reinforced concrete flat slab	9th	10th	10th	2nd
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	8th	7th	8th	7th
Option 9 Reinforced concrete waffle slab	10th	9th	9th	1st
Option 10 Pre-cast double T units on reinforced concrete edge beams	7th	8th	7th	7th

Table 5.5.2: Summary of ranking of options on criteria C3 & C4 in Dublin and Manchester

Structural Option	Frame const. time C3		Overall const. time C4	
	Dublin	Manchester	Dublin	Manchester
Option 1 Slimflor® beams and pre-cast hollowcore slab	2nd	4th	2nd	4th
Option 2 Slimflor® beams and deep deck floor (un-propped)	1st	1st	1st	1st
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	2nd	4th	4th	4th
Option 4 Composite beams and floor slab	2nd	4th	2nd	4th
Option 5 Cellular beams or castillated beams and composite slab	2nd	1st	4th	2nd
Option 6 Composite beams with web openings	2nd	1st	4th	2nd
Option 7 Reinforced concrete flat slab	9th	7th	9th	7th
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	7th	7th	8th	7th
Option 9 Reinforced concrete waffle slab	10th	10th	10th	10th
Option 10 Pre-cast double T units on reinforced concrete edge beams	7th	7th	7th	7th

6 Multi-Criteria Decision Analysis model (MCDA)

6.1 Introduction

The proper planning of a major engineering structure requires a set of procedures to be devised which ensures that available resources are allocated as efficiently as possible in its subsequent design and construction. This involves deciding how the available resources, including manpower, physical materials and finance can best be used to achieve the desired objectives of the project developer. Engineering systems analysis provides an orderly process in which all factors relevant to the design and construction of the structure can be considered.

The planning of an engineering project is a rational process. It involves a project's developer acting or deciding rationally in an attempt to reach some goal that cannot be attained without some action. He must have a clear awareness of alternative paths by which agreed goals can be achieved and must have both the information and the ability to analyse and evaluate options in relation to the goals sought. It is a problem solving process which involves looking at the developer's objectives and applying them to the future development. The objectives may be, for example, less expensive form of construction, reduced construction time or a more sustainable structure. The basic procedure can be represented by five fundamental steps (Rogers, 2001). They constitute the foundation of a systematic analysis and can be listed as follows;

- Definition of goals and objectives
- Formulation of criteria
- Generation of alternatives
- Evaluation of alternatives
- Selection of preferred alternatives

6.2 Define Objectives

No planning process should proceed without an explicit statement of the objectives, goals or overall purpose of the proposed undertaking. These objectives will each have their own merits and must be considered by their own individual set of criteria. The objectives serve to define the desired situation that will transpire as a direct result of the construction of the proposed project.

6.3 Formulate Criteria

Defining the planning problem involves identifying the actual gap between the desired situation, as defined by the set of objectives derived, and the current situation, and assembling a range of measures designed to minimise or even close it. Measures of performance, or criteria, must therefore be determined. They are used as "standards of judging" in the case of the options being examined. The selection of criteria for the evaluation of alternatives is of crucial importance to the overall process, because it can influence, to a very great extent, the final design. This selection process is also of value because it decides, to a large degree, the final option chosen.

6.4 Generation of Alternatives

The ultimate end point of the process is to identify a preferred solution. It is logical that the decision maker should invest substantial effort in examining a broad range of feasible options. Since it would not be possible or feasible to subject all possible options to a thorough analysis the decision maker must always be selective in the choice of options considered within the process. The decision maker must also pay particular attention to identifying those alternatives that are shown to be most productive in achieving objectives, while ensuring that effort spent on the analysis of a given alternative does not exceed its anticipated benefits. This process should result in the drawing up of a set of alternative proposals, each of which would reasonably be expected to meet the objectives stated.

6.5 Evaluation of Alternatives

The relative merit of each option is determined on the basis of its performance on each of the chosen criteria. Each option is aligned with the selected criteria. This process is usually undertaken using some form of mathematical model. Selecting the appropriate model for the decision problem under consideration is a key step in the evaluation process.

6.6 Selection

This is the stage at which a short list is made of the various options which are most likely to bring about the objectives agreed at the start of the process.

In order to guide a decision maker in choosing the most appropriate option at the evaluation stage, a set of rules is required to interpret the criterion evaluations for each of the options considered. The challenge is to develop an evaluation procedure appropriate for both the decision problem under consideration and the available information. The set of decision rules at the basis of the evaluation process is of vital importance.

Multi-criteria decision aid gives project planners some technical tools in order to help them solve a decision problem where several often conflicting and opposing points of view must be taken into account within the decision process. In many cases no single option exists which is the best in economic, technical and environmental terms. The word 'aid' within the description of the methodology emphasises the virtual impossibility of providing a truly scientific foundation for an optimal solution. Multi-criteria Decision Aid provides procedures to help maintain the 'desired situation', as expressed in the set of objectives, in the presence of ambiguity and uncertainty. However refined models may be, it must be recognised that no amount of data will remove the fundamental uncertainties which surround any attempt to peer into the future.

Multi-criteria methods, which do not yield a single, 'objectively best' solution, but rather yield a list of preferred solutions or a general ranking of all options, are the most readily applicable models to problems of option choice within civil and structural engineering where it is virtually impossible to provide a scientific basis for an optimum solution. Solving a multi-criteria problem is actually helping the decision maker to master the complex data involved in a decision problem and advance towards a solution. This process involves compromise whereby the Multicriteria aid gives project planners some technical tools in order to enable them to solve a decision problem where several often conflicting and opposite points of view must be taken into account within the decision process. In many cases no single option exists which is the best in economic, technical and environmental terms. It depends on the personality of the decision maker and on the circumstances in which the decision aiding process is taking place. However complete the information, the need for personal judgement and experience in making project planning decisions remains.

Multi-criteria decision aid begins with the generation of criteria that should provide a means of evaluating the extent to which each option achieves the goal or the 'desired situation'.

The four criteria chosen for this study are shown and identified as

C1 Cost

C2 Initial embodied energy

C3 Frame construction time

C4 Overall construction time

It is vital that the criteria chosen represent the desired ultimate goal of the decision makers and that they have the following basic properties:

- ***Be complete and exhaustive***: All important performance attributes deemed relevant to the final solution must be represented by the criteria on the list.
- ***Be mutually exclusive***: This permits the decision maker to view the criteria as independent entities among which appropriate 'trade offs' may subsequently be made.
- ***Be restricted to performance attributes of real importance to the decision problem***: This provides a sound starting point for the problem, as the less important or irrelevant or un-necessary criteria can be screened out of the process at the earliest possible stage.

The ten structural options are shown and identified as

S1 Slimflor® beams and pre-cast hollow core slab

S2 Slimflor® beams and deep deck floor un-propped

S3 Slimflor® beams and deep deck floor propped

S4 Composite beams and composite floor slab

S5 Cellular beams or castellated beams and composite slab

S6 Composite beams with web openings

S7 Reinforced concrete flat slab

S8 Pre-cast hollow core units on reinforced concrete edge beams

S9 Reinforced concrete waffle slab

S10 Precast double T units on reinforced concrete edge beams

6.7 Models used within the study

6.7.1 Introduction

The models applied in this study are:

- The Borda method
- The Dominance method
- The Promethee 1 method

Tables 6.7.1.1 and 6.7.1.2 give the rankings of the four decision groups for Dublin and Manchester respectively. These tables should be referred to when reading through the methodology involved for each of the three decision models.

Table 6.7.1.1: Ranking results (Dublin)

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4
Option 1 (S1)	1	2	2	2
Option 2 (S2)	4	6	1	1
Option 3 (S3)	3	4	2	4
Option 4 (S4)	2	1	2	2
Option 5 (S5)	5	3	2	4
Option 6 (S6)	6	5	2	4
Option 7 (S7)	9	10	9	9
Option 8 (S8)	8	8	7	8
Option 9 (S9)	10	9	10	10
Option 10 (S10)	7	7	7	7

Table 6.7.1.2: Ranking results (Manchester)

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4
Option 1 (S1)	2	3	4	4
Option 2 (S2)	4	6	1	1
Option 3 (S3)	3	4	4	4
Option 4 (S4)	1	5	4	4
Option 5 (S5)	5	9	1	2
Option 6 (S6)	6	10	1	2
Option 7 (S7)	10	2	7	7
Option 8 (S8)	7	7	7	7
Option 9 (S9)	9	1	10	10
Option 10 (S10)	8	7	7	7

6.7.2 The Borda Method

The Borda method (Vincke, P, 1992) is a simple rudimentary way of assessing the ranking of a number of options. The results are blunt and not very refined but can give some idea as to what will possibly be the most favoured options when a more accurate model is used. It is somewhat comparable to an engineer doing a 'back of an envelope' calculation for a steel or concrete beam. A size of beam can be chosen quickly and may be all the architect or services engineer needs to know. However, the engineer will need to carry out further and more accurate calculations to satisfy all design criteria.

For each criterion the options are ranked first to last and the overall score for each option is obtained by adding each of its ranking scores together. This technique involves a system where a number of ranks are summed together as a form of weighted average. Within it the *n* rankings (in this situation *n* is 10 as it represents the number of options) are aggregated to give an overall ranking. The option with the lowest score is ranked first, the second lowest ranked second, the third lowest ranked third etc.

For example, consider the rankings of options S1 and S4 in relation to cost, initial embodied energy, frame construction time and overall construction time for Dublin and Manchester. The results are tabulated below:

Borda Method (Dublin)-ranking results

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4	Sum	Rank Position
Option 1 (S1)	1	2	2	2	**7**	**1st**
Option 4 (S4)	2	1	2	2	**7**	**1st**

Borda Method (Manchester)-ranking results

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4	Sum	Rank Position
Option 1 (S1)	2	3	4	4	**13**	**1st**
Option 4 (S4)	1	5	4	4	**14**	**2nd**

For Dublin, it is not possible to say which of the options is the preferred solution as neither option performs better overall than the other. Although the criteria are not ranked similarly for each option the added total of the rankings is the same. For Manchester the preferred option is S1.

It is a blunt instrument because it is assumed that all criteria are of equal importance, and it generates a numerical or cardinal score from what is in essence a ranking number. The rankings give no information on the extent of the difference between the options ranked 1 and 2 or the options ranked 2 and 3.

6.7.3 The Dominance Method

This model can be described as a simple 'non-compensatory' method because selection of the preferred option does not involve trading off the disadvantages of one criterion against the advantages of another. Superiority in one criterion cannot be offset by an inferior performance on some other one. It is, therefore, a relatively simple method but one which produces less ranking information than the more complex methods such as Promethee. (i.e. more options are likely to remain unranked).

An option is said to be dominated if another option exists that performs better than it on one or more of the decision criteria and equals it on the remainder. It is in effect, a screening process where the options being evaluated are reduced to a short list by eliminating all those that are dominated.

The screening process proceeds as follows:

1. Compare the first two options; if one is dominated by the other, discard the dominated one.
2. Compare the un-discarded option with the third option and again discard the dominated one.
3. Introduce the fourth option and so on as before.
4. If the process involves *n* project options, the process requires *n*-1 steps. For this study *n*-1 is 10-1 i.e. 9.

In order to explain this further, refer to the chart below which shoes the ranking of options S1, S3, S7 and S9 for Dublin.

Dominance Chart (Dublin)-Ranking Results

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4
Option 1 (S1)	1	2	2	2
Option 3 (S3)	3	4	2	4
Option 7 (S7)	9	10	9	9
Option 9 (S9)	10	9	10	10

S1 performs better than option S3 for criteria C1, C2 and C4 and is equal to option C3 on the remaining criterion C3. Therefore option S1 dominates option S3. S1 is also better than options S7 and S9 on all criteria. Option S1 is the preferred option as none of the other options perform better than it on the four criteria. Option S3 performs better than options S7 and S9 on all criteria and can therefore be considered the second preferred option. Option S7 is better than option S9 on criteria C1, C3 and C4. If option S7 is to dominate S9 it would have to have an equal ranking for criterion C2. Since option S9 performs better than option S7 for criterion C2, it is not possible to say which of these options is the preferred solution and therefore options S7 and S9 cannot be ranked relative to one another. The final result, for this sample, using the Dominance method is:

1st Option S1

2nd Option S3

3rd Option S7 and option S9

6.7.4 Promethee 1 Method

6.7.4.1 Concordance Analysis

Often a decision maker may require a decision method that generates a simple ranking of the various options involved rather than an actual score for each. In such a situation, Concordance Analysis may be the most appropriate decision model. It is a suitable methodology in situations where it may not be necessary to know the relative positions in the final hierarchy of all options. For example, if it is known that option *a* is better than options *b* and *c*, the relative positions of b and c may be irrelevant to the decision maker. It should be possible for the two to remain incomparable without endangering the decision process.

In some engineering situations it may actually be quite useful to highlight the incomparability of a number of options because of the absence of sufficient information to allow a realistic solution given the quality of data available. If the information is not of a sufficiently high quality to produce a ranking directly connecting all options, then what is termed a 'partial ranking' will be derived where some options are not directly compared. In practice, concordance techniques are generally used to produce a shortlist of preferred options from a relatively large number of project options rather than one single 'best project option'.

Concordance Analysis is termed a non-compensatory multi-criteria decision making model. It utilises a number of mathematical functions to indicate the degree of dominance one option or group of options has over others under consideration. Within this form of analysis there is no 'trading off' of one criterion directly against another for each individual option.

The comparison of project options takes place on a pair-wise basis with respect to each criterion (a pair-wise dominance relationship between options), and establishes the degree of dominance that one option has over another. The main measure of this dominance of one option over another is the *concordance score.* For a given pair of options (*a,b*), comparison of their relative performance takes place on each individual criterion. As a result, a picture of the level of dominance of *a* over *b* is constructed.

For example, consider Dublin options S1, S3, S4 and S6 and the criteria C1, C2, C3 and C4. The concordance indices/matrices are set up by giving the value 1 to the option which is ranked higher than another option for each of the criteria. A value of 1 is also given where the two options are ranked equal on a particular criterion. For a given option, the sum of the scores along its row indicates the extent to which it is better than the other option, while the sum of the scores along its column is an indication of the degree to which the other option is better than it. The greater the option's row score and the smaller its column score, the better its ranking.

Criterion – Cost C1

	(S1)	(S3)	(S4)	(S6)
(S1)	1	1	1	1
(S3)	0	1	0	1
(S4)	0	1	1	1
(S6)	0	0	0	1

Criterion – Initial embodied energy C2

	(S1)	(S3)	(S4)	(S6)
(S1)	1	1	0	1
(S3)	0	1	0	1
(S4)	1	1	1	1
(S6)	0	0	0	1

Criterion – Frame construction time C3

	(S1)	(S3)	(S4)	(S6)
(S1)	1	1	1	1
(S3)	1	1	1	1
(S4)	1	1	1	1
(S6)	1	1	1	1

Criterion Overall construction time C4

	(S1)	(S3)	(S4)	(S6)
(S1)	1	1	1	1
(S3)	0	1	1	1
(S4)	1	1	1	1
(S6)	0	1	0	1

Consider criterion C1 and add the rows and columns of all the options. The sum of the row for S1 is 4 and the sum of the column is 1, the sum of the row for S4 is 3 and the sum of the column is 2 etc. Option S1 dominates the other structural forms in relation to cost as its row score is the greatest and its column score the smallest. Now consider criterion C2 and carry out the same exercise. Option 4 has the highest row score and the smallest column score. It therefore dominates the other options in terms of initial embodied energy. Reference to criterion C3 shows that the sum of the rows and the columns for all options is the same. This indicates that no one option dominates the other in relation to frame construction time and it would be therefore impossible to determine the preferred option based on this criterion only.

This data or concordance indices/matrices for all criteria now needs to be combined to give an overall indication of the dominance of all pairs of options (*b* by *a*). This is achieved by the use of the relative importance weightings for the criteria and by using one of a number of weighting systems, the order of dominance can be drawn up. For this study the Direct Weighting System is adapted.

6.7.4.2 Weighting Criteria

The assignment of importance weightings to each criterion is a crucial step in the application of multi-criteria analysis. 'Weights' used are simply a measure of the relative importance of the criteria involved. Vincke (1992) compares the weighting of a criterion to the number of votes given to a candidate in a voting procedure, with the final tally indicating the relative importance of each criterion 'candidate'.

The method which is used in this project to weight criteria is referred to as the 'direct weighting system'. This method is simple and straightforward; the decision maker expresses his/her preference by assigning weights directly to the criteria. The requirement for a nine-point scale is based on Saaty's belief that, within the framework of a simultaneous comparison, one does not need more than nine scale points to distinguish between stimuli (Saaty, 1977). Results from psychological studies (Miller, 1956) have shown that a scale of about seven points was sufficiently discerning.

Hokkanen and Salminen (1994) used this method in their selection of a solid waste system. In their study they requested 45 decision makers to scale each criterion from 1 to 7, 7 being the most important. In parallel, they used a second procedure where each decision maker was asked to give the numeral '1' to the least important criterion, and then base the other importance values on how many times more important they appeared to be than the least important one. Hokkanen and Salminen found that, the two sets of weights were normalised, there were only minor differences between the two procedures.

6.7.4.3 Multi Criteria Decision Model

Once the pair-wise dominance relationship between options has been established by means of the index scores within each of the four concordance matrices, it is then required to establish a relative ranking of the proposals based on these dominance scores. One of the most straightforward ways of compiling the ranking hierarchy is the system put forward by Brans & Vincke (1985) as part of their Promethee 1 Decision Model.

This is done by multiplying the values in each concordance matrix by the normalised weight assigned by the decision maker. This is known as the weighted matrix. The overall weighted matrix is formed by adding the concordance scores of the individual weighted matrices. The sum of the rows and the sum of the columns is established. This is a crucial step in the application of multi-criteria analysis. 'Weights' used are simply a measure of the relative importance of the criteria involved.

Promethee 1 uses this property by taking each option's row score and ranking each option, placing the one with the highest score first, the one with the next highest score second, and so on until all are ranked. The method then takes the column scores and places the option with the highest score last, the one with the next highest score second last, and so on. A final ranking is obtained by finding the intersection between these two separate rankings.

The study uses this method by carrying out the following steps:

1. Add together the sum of the rows of each option
2. Add together the sum of the columns of each option
3. Subtract the sum of the rows and the columns for each option
4. The option with the highest score is the preferred solution and the option with the lowest score is the least preferred option

This final result can yield a partial pre-order, as incomparabilities between options may occur due to possible conflicts between the two rankings.

7 Results of the decision modelling process

7.1 Borda Method

Tables 7.1.1 and 7.1.2 give the rankings of the four decision criteria for Dublin and Manchester respectively. These have been summed to give an overall score, with the lowest sum being ranked first, the second lowest ranked second, etc.

In Dublin the structural forms ranked joint first are option S1, slimflor® beams and pre-cast hollow core slab, and option S4, composite beam and floor slab. In Manchester the preferred structural alternative is option S2, slimflor® beams and deep deck floor un-propped, while option S1 is ranked in second place. Option S2 and option S4 are ranked third in Dublin and Manchester respectively. Option S3, slimflor® beams and deep deck floor propped, is placed in fourth position in both locations.

Although the four highest ranked options in Dublin and Manchester are the same the individual rankings for each of the decision criteria are quite diverse. In Dublin options S1 and S4 score highest for cost and initial embodied energy and only drop second place to option S2 for frame and overall construction times. None of their criteria rankings fall below second place. Options S2 and S3 do not score well for initial embodied energy and option S3 drops to fourth place for overall construction time. The gap between the sum of the ranking of the two preferred options S1 and S4 and the next two preferred structural alternatives S2 and S3 is significant and makes the selection process easy.

In Manchester the preferred option S2 does not score well for cost and initial embodied energy but ranks first for frame construction time and overall construction time. Option S1 scores much better than option S2 for cost and initial embodied energy but lies in fourth place for frame construction time and overall construction time. Option S4 is first for cost and fourth for frame construction time and overall construction time. The gap between the sum of the rankings of options S1, S3 and S4 is very close and therefore the selection process is not as clear cut.

This selection model does not allow the decision maker to consider the relative importance of each of the criteria. For example, in Manchester, option S4 ranks first for cost and fifth for initial embodied energy and yet it is in third position overall. Option S2 is ranked in fourth position for cost and in sixth position for initial embodied energy. Option S4 would appear to be the preferred option but once the ranking for frame construction time and overall construction time is considered this option drops to third place and option S2 goes into first place. Cost is not considered more important than frame construction time or vice versa.

In both locations the concrete options rank behind the steel alternatives. In Dublin the preferred concrete form is option S10, pre-cast double T units on reinforced concrete edge beams and the least preferred frame is option S9, reinforced concrete waffle slab. Option S10 ranks better than the other concrete alternatives for cost, initial embodied energy and overall construction time and equals option S8, pre-cast hollow core units on reinforced concrete beams, for frame construction time.

In Manchester option S7, reinforced concrete slab, is the selected concrete form. It is ranked higher than in Dublin and this is due to it being placed second for initial embodied energy. The least preferred option is S9, reinforced concrete waffle slab, which is the same as for Dublin.

Table 7.1.1: Borda Method (Dublin)-ranking results

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4	Sum	Rank Position
Option 1 (S1)	1	2	2	2	**7**	**1st**
Option 4 (S4)	2	1	2	2	**7**	**1st**
Option 2 (S2)	4	6	1	1	**12**	**3rd**
Option 3 (S3)	3	4	2	4	**13**	**4th**
Option 5 (S5)	5	3	2	4	**14**	**5th**
Option 6 (S6)	6	5	2	4	**17**	**6th**
Option 10 (S10)	7	7	7	7	**28**	**7th**
Option 8 (S8)	8	8	7	8	**31**	**8th**
Option 7 (S7)	9	10	9	9	**37**	**9th**
Option 9 (S9)	10	9	10	10	**39**	**10th**

Table 7.1.2: Borda Method (Manchester)-ranking results

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4	Sum	Rank Position
Option 2 (S2)	4	6	1	1	**12**	**1st**
Option 1 (S1)	2	3	4	4	**13**	**2nd**
Option 4 (S4)	1	5	4	4	**14**	**3rd**
Option 3 (S3)	3	4	4	4	**15**	**4th**
Option 5 (S5)	5	9	1	2	**17**	**5th**
Option 6 (S6)	6	10	1	2	**19**	**6th**
Option 7 (S7)	10	2	7	7	**26**	**7th**
Option 8 (S8)	7	7	7	7	**28**	**8th**
Option 10 (S10)	8	7	7	7	**29**	**9th**
Option 9 (S9)	9	1	10	10	**30**	**10th**

Figure 7.1.1 presents graphically the relative difference between the sum of the rankings on the four criteria for the structural alternatives in Dublin and Manchester. The difference between the sum of the rankings for the steel options and the sum of the rankings for the concrete options in Dublin is far greater than in Manchester. This suggests that the selection of the optimum solution in Manchester is more difficult as one option is not clearly better than the other.

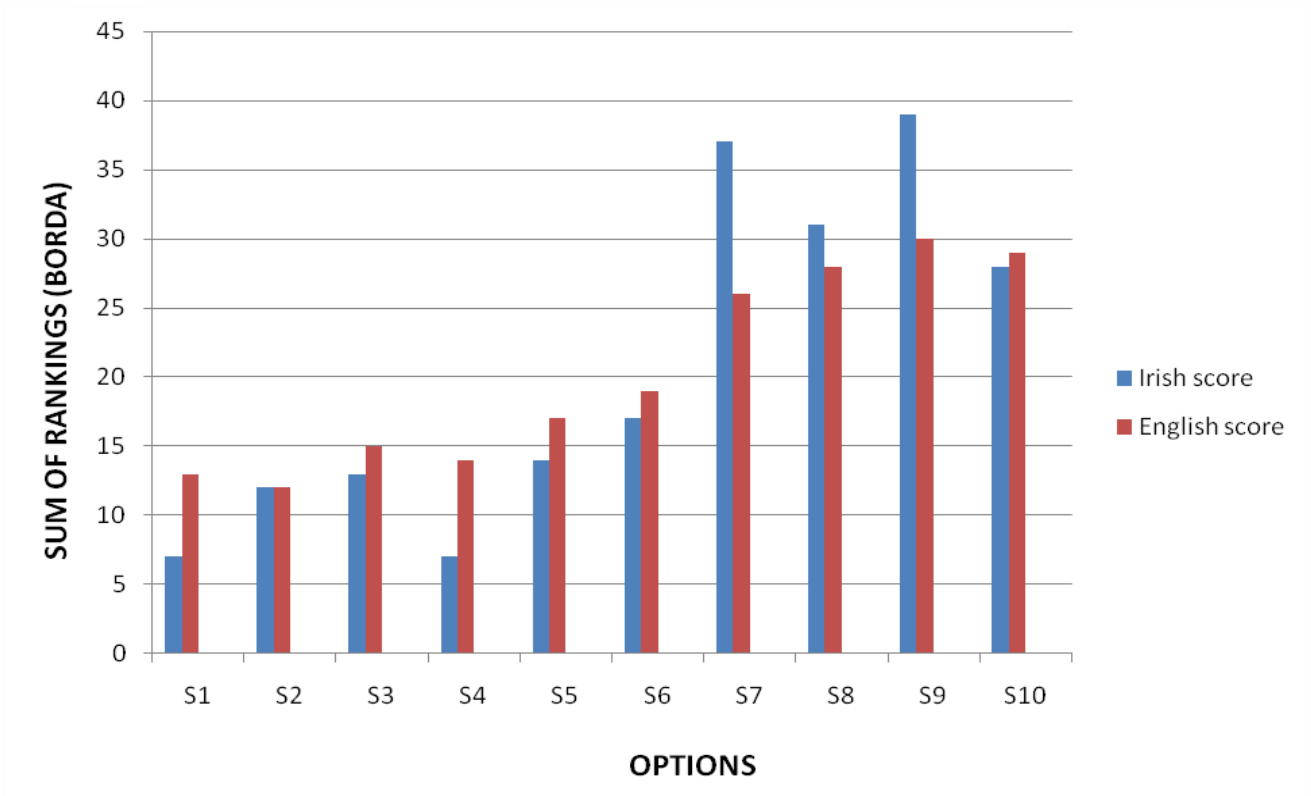

Figure 7.1.1 Comparison of rankings in Dublin and Manchester – Borda method

7.2 Dominance Method

Dublin Analysis

Table 7.2.1 gives the Dublin scores for the ten design options on each of the four criteria. Table 7.2.2 shows the pairwise dominance relationship between the options in Dublin. This table is produced by establishing the dominance of one option over another on the four criteria. As discussed in chapter 6 an option is said to be dominated if another option exists that performs better than it on one or more of the decision criteria and equals it on the remainder.

Consider, for example, option S5, cellular beams or castellated beams and composite slab and option S7, reinforced concrete flat slab. Option S5 dominates option S7 because it ranks better than option S7 on all four criteria. Option 5 performs better than option S3, slimflor® beams and deep deck floor propped, for initial embodied energy and equals it for frame construction time and overall construction time but does not perform as well for cost. Therefore option S5 does not dominate option S3.

This process is carried out for all options until Table 7.2.2 is completed. The dominance relationships are shown in Figure 7.2.1

Three of the options, S1, slimflor® beams and pre-cast hollow core slab, S2, slimflor® beams and deep deck floor un-propped, and S4, composite beams and floor slab, are not dominated, and constitute the shortlist of preferred options. It does not indicate the order of ranking of the three options. All others are dominated:

- Option S3 and option S5 are dominated by option S1 and option S4
- Option S6 is dominated by option S3, option S5, option S1 and option S4
- Option S10 is dominated by option S6, option S3, option S5, option S1, option S4 and option S2
- Option S8 is dominated by option S10, option S6, option S3, option S5, option S1, option S4 and option S2
- Option S7 and Option S9 are dominated by option S8, option S10, option S6, option S3, option S5, option S1, option S4 and option S2

Figure 7.2.1 shows that option S3 and option S5 do not dominate the other. The two structural forms are said to be incomparable. This means that one cannot be considered more preferable than the other. The same applies to option S7 and S9, reinforced concrete waffle slab. Option S2 neither dominates or is dominated by options S1, S4, S3, S5 and S6, composite beams with web openings, and is therefore not comparable with these options.

The three preferred structural options in Dublin using the Dominance method are as follows:

- **Option 1 (S1)** Slimflor® beams and pre-cast hollow core slab
- **Option 4 (S4)** Composite beams and floor slab
- **Option 2 (S2)** Slimflor® beams and deep deck floor (un-propped)

The least favoured options from the Dominance chart are option S7, reinforced concrete flat slab and option S9, reinforced concrete waffle slab.

Table 7.2.1: Dominance Chart (Dublin)-Ranking Results

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4
Option 1 (S1)	1	2	2	2
Option 2 (S2)	4	6	1	1
Option 3 (S3)	3	4	2	4
Option 4 (S4)	2	1	2	2
Option 5 (S5)	5	3	2	4
Option 6 (S6)	6	5	2	4
Option 7 (S7)	9	10	9	9
Option 8 (S8)	8	8	7	8
Option 9 (S9)	10	9	10	10
Option 10 (S10)	7	7	7	7

Table 7.2.2: Pairwise dominance relationship between options (Dublin)

		DOMINATED OPTIONS									
		S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
	S1	-	NO	YES	NO	YES	YES	YES	YES	YES	YES
	S2	NO	-	NO	NO	NO	NO	YES	YES	YES	YES
	S3	NO	NO	-	NO	NO	YES	YES	YES	YES	YES
DOMINATING	**S4**	NO	NO	YES	-	YES	YES	YES	YES	YES	YES
OPTIONS	**S5**	NO	NO	NO	NO	-	YES	YES	YES	YES	YES
	S6	NO	NO	NO	NO	NO	-	YES	YES	YES	YES
	S7	NO	NO	NO	NO	NO	NO	-	NO	NO	NO
	S8	NO	NO	NO	NO	NO	NO	YES	-	YES	NO
	S9	NO	NO	NO	NO	NO	NO	NO	NO	-	NO
	S10	NO	NO	NO	NO	NO	NO	YES	YES	YES	-

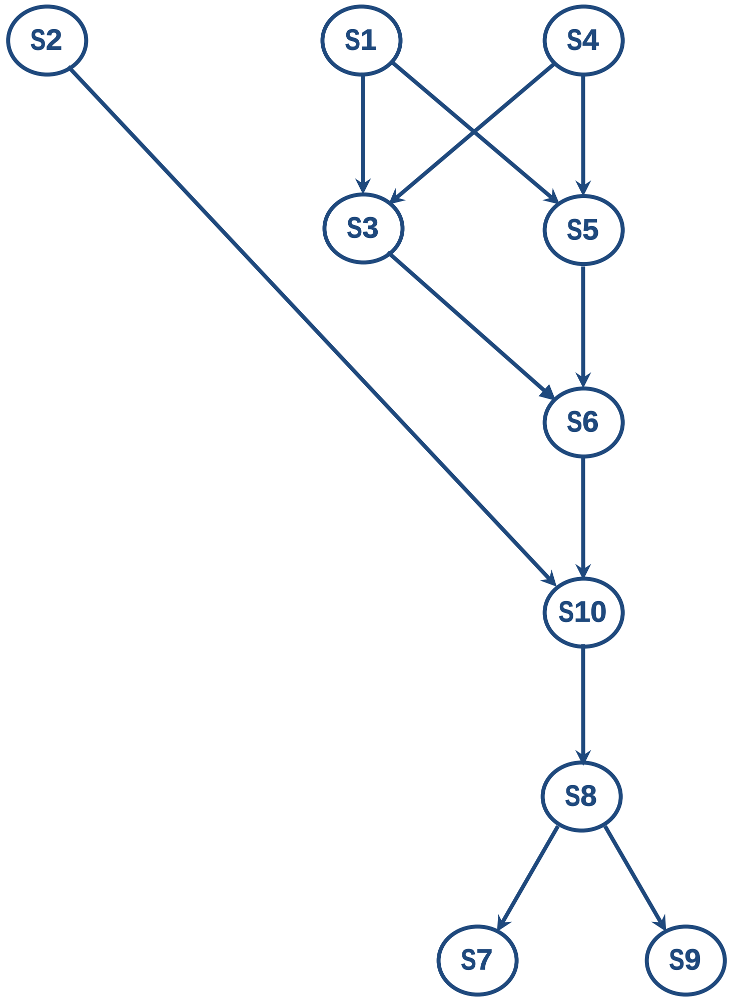

Figure 7.2.1: Dominance results for Dublin data

In Dublin, the preferred structural alternatives are clearly options S1, slimflor® beams and pre-cast hollow core slab, and S4, composite beams and floor slab. Option S2, slimflor® beams and deep deck floor un-propped, is on the shortlist of possible solutions and yet it does not dominate options S3, slimflor® beams and deep deck floor propped, S5, cellular beams or castellated beams and composite slab, and S6, composite beams with web openings. It ranks behind these three forms on initial embodied energy and behind option S3 on cost but is the preferred option for speed of frame construction and overall construction time. Since this form of multi criteria decision analysis does not recognise the importance of one criterion over the other, incomparabilities like this can occur. The placement of option S2 on the shortlist would be the responsibility of the decision maker. If he/she regards frame construction time and overall construction time as essential to the project then this option would have to be considered.

Manchester Analysis

Table 7.2.3 gives the Manchester rankings for the ten design options on each of the four criteria. Table 7.2.4 shows the pairwise dominance relationship between the options. The dominance relationships are shown in Figure 7.2.2

The ranking of the various structural forms for Manchester, using the Dominance method, is not conclusive. The decision maker would have difficulty in selecting a design scheme without explicit information regarding the relative importance of the criteria used within this analysis.

- Option S3 is dominated by option S1
- Option S5 is dominated by option S2
- Option S8 and option S10 are dominated by option S2, option S3 and option S4
- Option S5 is dominated by option S2
- Option S6 is dominated by option S5

While the short listing of non-dominated options may appear to be a rational attempt to isolate the better performing proposals under examination, some dominated options might, in overall terms, be better than some of the non-dominated options. For example, option S9 is non-dominated, even though it performs considerably worse than the dominated options S3, slimflor® beams and deep deck floor propped, S5, cellular beams or castellated beams and composite slab, S8, pre-cast hollow core units on reinforced concrete edge beams, and S10, pre-cast double T units on reinforced concrete edge beams, for criteria C1, cost, C3, frame construction time, and C4, overall construction time. It remains non-dominated as it is ranked in first place for initial embodied energy. This could lead to difficulty and uncertainty for the decision maker in selecting the optimum structural form.

The five preferred structural options in Manchester using the Dominance method are as follows:

- **Option 1 (S1)** Slimflor® beams and pre-cast hollow core slab
- **Option 2 (S2)** Slimflor® beams and deep deck floor (un-propped)
- **Option 4 (S4)** Composite beams and floor slab
- **Option 7 (S7)** Reinforced concrete flat slab
- **Option 9 (S9)** Reinforced concrete waffle slab

It is up to the decision maker to decide which of these options is the optimum solution. Options S7 and S9 rank lowest for cost, frame construction time and overall construction time and second and first respectively for initial embodied energy. The decision maker would have to ask himself/herself how significant this criterion is to the selection process. For example, if he/she concludes that the cost of the structural frame is more important than the initial embodied energy, then options S7 and S9 can be disregarded. If initial embodied energy is considered more significant then these options can be shortlisted with options S1, S2 and S4.

In Dublin this incomparability does not exist as options S7 and S9 are ranked lowest for all criteria and can therefore be disregarded by the decision maker.

Table 7.2.3: Dominance Chart (Manchester)-Ranking Results

STRUCTURAL OPTION	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4
Option 1 (S1)	2	3	4	4
Option 2 (S2)	4	6	1	1
Option 3 (S3)	3	4	4	4
Option 4 (S4)	1	5	4	4
Option 5 (S5)	5	9	1	2
Option 6 (S6)	6	10	1	2
Option 7 (S7)	10	2	7	7
Option 8 (S8)	7	7	7	7
Option 9 (S9)	9	1	10	10
Option 10 (S10)	8	7	7	7

Table 7.2.4: Pairwise dominance relationship between options (Manchester)

		DOMINATED OPTIONS									
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
DOMINATING OPTIONS	S1	-	NO	YES	NO	NO	NO	NO	YES	NO	YES
	S2	NO	-	NO	NO	YES	YES	NO	YES	NO	YES
	S3	NO	NO	-	NO	NO	NO	NO	YES	NO	YES
	S4	NO	NO	NO	-	NO	NO	NO	YES	NO	YES
	S5	NO	NO	NO	NO	-	YES	NO	NO	NO	NO
	S6	NO	NO	NO	NO	NO	-	NO	NO	NO	NO
	S7	NO	NO	NO	NO	NO	NO	-	NO	NO	NO
	S8	NO	NO	NO	NO	NO	NO	NO	-	NO	NO
	S9	NO	NO	NO	NO	NO	NO	NO	NO	-	NO
	S10	NO	NO	NO	NO	NO	NO	NO	NO	NO	-

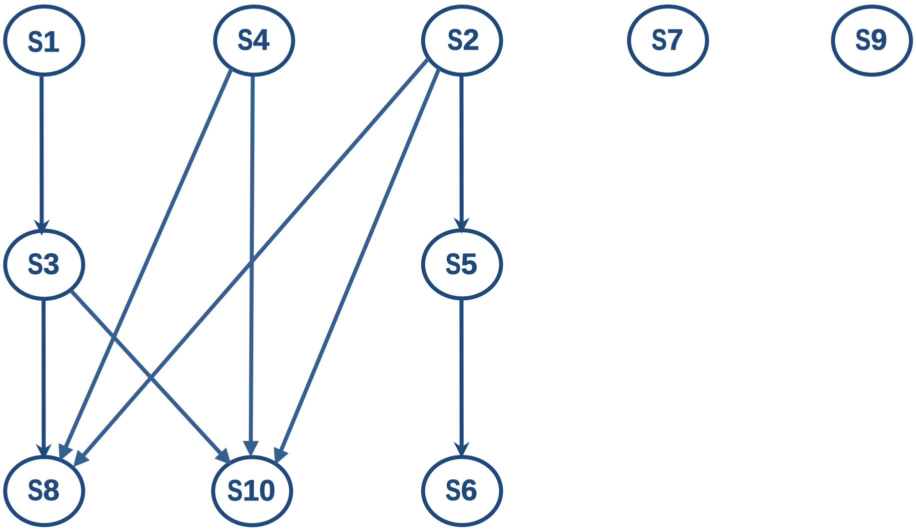

Figure 7.2.2: Dominance results for Manchester data

7.3 Promethee 1 Model

The twenty one decision makers involved in the selection process included structural engineers, architects, quantity surveyors, planners and developers/contractors. They were asked to assign weightings to each of the four criteria C1, cost, C2, initial embodied energy, C3, frame construction time and C4, overall construction time. The criteria were scored from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion. This is discussed in 6.7.4.2.

Appendix A contains the survey results of all twenty one decision makers. Table 7.3.1 shows the discipline of each of the decision makers and the weightings applied to the 4 criteria. Due to the variation in expertise amongst the decision makers, there is quite a contrast amongst the weightings assigned by each of them to the four criteria.

For example, a developer/ contractor will not want to spend any more time on site than is necessary. Some contracts have a built-in clause whereby the contractor is paid an agreed sum if the contract is finished before the programmed end date. The contractor would therefore be expected to assign the greatest weighting to the overall construction time. On the other hand, the engineer and architect who are the client's representative and who look after quality and expenses, would probably give the highest weighting to cost.

The values show that ten of the decision makers give the highest weighting to cost, while only one of the decision makers chooses initial embodied energy as the most important criterion. Sixteen of the stakeholders consider criterion C2 to be the least important. None of the decision makers rate frame construction time as the most important criteria although four of them give the highest weighting to overall construction time.

The normalised weighting given to each criterion is found by adding the points assigned to the four criteria to give a total and dividing the points given to each criterion by that total.

The normalised weighting for each of the twenty one decision makers are set out in Table 7.3.1.

Table 7.3.1: Normalised weighting applied by the Decision Makers

Decision Makers		Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4
DM1	Engineer	0.39	0.17	0.17	0.28
DM2	Engineer	0.30	0.22	0.22	0.26
DM3	Academic	0.37	0.16	0.21	0.26
DM4	Quantity surveyor	0.30	0.17	0.30	0.22
DM5	Developer	0.22	0.22	0.26	0.30
DM6	Engineer	0.33	0.14	0.26	0.27
DM7	Developer	0.18	0.12	0.29	0.41
DM8	Engineer	0.35	0.12	0.29	0.24
DM9	Architect	0.32	0.21	0.21	0.26
DM10	Quantity surveyor	0.43	0.07	0.21	0.29
DM11	Developer	0.28	0.16	0.28	0.28
DM12	Planner	0.29	0.17	0.29	0.25
DM13	Quantity surveyor	0.31	0.13	0.25	0.31
DM14	Quantity surveyor	0.41	0.06	0.24	0.29
DM15	Developer	0.31	0.13	0.25	0.31
DM16	Engineer	0.32	0.14	0.23	0.32
DM17	Architect	0.24	0.19	0.24	0.33
DM18	Planner	0.42	0.25	0.17	0.17
DM19	Academic	0.22	0.30	0.22	0.26
DM20	Architect	0.33	0.19	0.29	0.19
DM21	Developer	0.26	0.11	0.26	0.37

Tables 7.3.2 and 7.3.3 show the ranking of options 1 to 10, based on each of the four criteria as analysed for the Dublin and Manchester areas respectively. On the basis of both the derived rankings and the importance weightings assigned to each criterion by the decision makers, a set of concordance indices for each pair of options on each of the four decision criteria is compiled. This is done for each of the twenty one decision makers in Dublin and Manchester.

Table 7.3.2: Promethee 1 Method (Dublin)-Ranking Results

Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4
S1	S4	S2	S2
S4	S1	S1, S3, S4, S5,S6	S1, S4
S3	S5	S8 S10	S3,S5,S6
S2	S3	S7	S10
S5	S6	S9	S8
S6	S2		S7
S10	S10		S9
S8	S8		
S7	S9		
S9	S7		

Table 7.3.3: Promethee 1 Chart (Manchester)-Ranking Results

Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4
S4	S9	S2, S5, S6	S2
S1	S7	S1 , S3, S4	S5, S6
S3	S1	S7, S8, S10	S1, S3,S4
S2	S3	S9	S7, S8,S10
S5	S4		S9
S6	S2		
S8	S8,S10		
S10	S5		
S9	S6		
S7			

The concordance index can be expressed in mathematical form as follows. Assuming each criterion is assigned a weight w_j (j = 1,n, where n = number of criteria), increasing with the importance of the criterion, the concordance index for each ordered pair (a,b) can be rewritten as follows:

$C(a,b) = \frac{1}{W} \sum_{j:g_j(a) \geq g_j(b)} w_j$

Where

$W = \sum_{j=1}^{n} w_j$

and $g_j(a)$ is the score for criterion j under option a and $g_j(b)$ is the score for criterion j under option b.

$C(a,b)$ has a value between 0 and 1, and measures the strength of the statement 'option a outranks option b'.

Tables 7.3.4 to 7.3.11 set out the method by which the four concordance indices/matrices are compiled for each of the stakeholders by taking decision maker DM8 as an example. The normalised weightings assigned by decision maker DM8 to each of the four criteria are shown in Table 7.3.1 and the ranking of the options in Dublin are presented in Table 7.3.2

The first step is to establish the concordance matrix for criterion C1, cost. This is done by giving the value 1 to the option which is ranked higher than another option. A value of 1 is also given where two options are ranked equal on that criterion.

For example, option S1 is ranked higher than all other options. The number 1 is inserted at the intersection with the other options. Option S2 is ranked higher than options S5, S6, S7, S8, S9 and S10. The number 1 is now inserted where these options intersect with option S2. Option S2 ranks lower than options S1, S3 and S4. Zero is inserted where these options intersect with option S2. This process is continued until all the concordance scores are established. Refer to Table 7.3.4.

Table 7.3.4: Criterion C1 – Cost Concordance matrix (Dublin)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)
(S1)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
(S2)	**0**	**1**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
(S3)	0	1	1	0	1	1	1	1	1	1
(S4)	0	1	1	1	1	1	1	1	1	1
(S5)	0	0	0	0	1	1	1	1	1	1
(S6)	0	0	0	0	0	1	1	1	1	1
(S7)	0	0	0	0	0	0	1	0	1	0
(S8)	0	0	0	0	0	0	1	1	1	0
(S9)	0	0	0	0	0	0	0	0	1	0
(S10)	0	0	0	0	0	0	1	1	1	1

The next step is to multiply these concordance scores by the normalised weighting assigned to the criterion C1 by decision maker DM8. Reference to Table 7.3.1 shows this value to be 0.35. The scores along the rows and columns are added for each option.

For a given option, the sum of the scores along its row indicates the extent to which it is better than the other option, while the sum of the scores along its column is an indication of the degree to which the other option is better than it. The greater the option's row score and the smaller its column score, the better its ranking. This is shown in Table 7.3.5.

Table 7.3.5: Criterion C1 – Cost Weighted matrix (Dublin) DM8

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	***3.50***
(S2)	**0**	**0.35**	**0**	**0**	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	***2.45***
(S3)	0	0.35	0.35	0	0.35	0.35	0.35	0.35	0.35	0.35	***2.80***
(S4)	0	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	***3.15***
(S5)	0	0	0	0	0.35	0.35	0.35	0.35	0.35	0.35	***2.10***
(S6)	0	0	0	0	0	0.35	0.35	0.35	0.35	0.35	***1.75***
(S7)	0	0	0	0	0	0	0.35	0	0.35	0	***0.70***
(S8)	0	0	0	0	0	0	0.35	0.35	0.35	0	***1.05***
(S9)	0	0	0	0	0	0	0	0	0.35	0	***0.35***
(S10)	0	0	0	0	0	0	0.35	0.35	0.35	0.35	***1.40***
Total	***0.35***	***1.40***	***1.05***	***0.70***	***1.75***	***2.10***	***3.15***	***2.80***	***3.50***	***2.45***	

The preferred option in terms of cost is option S1 which has the highest row score and the lowest column score. The least preferred structural form is option S9 which has the lowest row score and the highest column score. It is not always the case that the row with the highest score corresponds with the column having the lowest score. In this instance the result gives a partial ranking. Promethee 1 brings the process forward and obtains a final ranking by finding the intersection between these two separate rankings. It is done by subtracting the column score of each option from its corresponding row score. The option with the highest score is considered the optimum solution.

The same procedure is carried out for criterion C2, initial embodied energy. For example, option S6 is ranked lower than options S1, S3, S4 and S5. Zero is inserted at the intersection of these options with option S6. Option S6 scores better than options S2, S7, S8, S9 and S10. The number 1 is now inserted at its intersection with these options. The process is continued until all the concordance scores are established. Refer to Table 7.3.6.

Table 7.3.6: Criterion C2 - Initial embodied energy Concordance matrix (Dublin)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)
(S1)	1	1	1	0	1	1	1	1	1	1
(S2)	0	1	0	0	0	0	1	1	1	1
(S3)	0	1	1	0	0	1	1	1	1	1
(S4)	1	1	1	1	1	1	1	1	1	1
(S5)	0	1	1	0	1	1	1	1	1	1
(S6)	**0**	**1**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**
(S7)	0	0	0	0	0	0	1	0	0	0
(S8)	0	0	0	0	0	0	1	1	1	0
(S9)	0	0	0	0	0	0	1	0	1	0
(S10)	0	0	0	0	0	0	1	1	1	1

It is now required to multiply these concordance scores by the normalised weighting assigned to the criterion C2 by decision maker DM8. Reference to Table 7.3.1 shows this value to be 0.12. The scores along the rows and columns are added for each option as shown in Table 7.3.7.

Table 7.3.7: Criterion C2 - Initial embodied energy Weighted matrix (Dublin) DM8

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	0.12	0.12	0.12	0	0.12	0.12	0.12	0.12	0.12	0.12	***1.08***
(S2)	0	0.12	0	0	0	0	0.12	0.12	0.12	0.12	***0.60***
(S3)	0	0.12	0.12	0	0	0.12	0.12	0.12	0.12	0.12	***0.84***
(S4)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	***1.20***
(S5)	0	0.12	0.12	0	0.12	0.12	0.12	0.12	0.12	0.12	***0.90***
(S6)	**0**	**0.12**	**0**	**0**	**0**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	***0.72***
(S7)	0	0	0	0	0	0	0.12	0	0	0	***0.12***
(S8)	0	0	0	0	0	0	0.12	0.12	0.12	0	***0.36***
(S9)	0	0	0	0	0	0	0.12	0	0.12	0	***0.24***
(S10)	0	0	0	0	0	0	0.12	0.12	0.12	0.12	***0.48***
Total	***0.24***	***0.72***	***0.48***	***0.12***	***0.36***	***0.60***	***1.20***	***0.96***	***1.08***	***0.84***	

The preferred option in terms of initial embodied energy is option S4 which has the highest row score and the lowest column score. The least preferred structural form is option S7 which has the lowest row score and the highest column score.

A similar procedure is carried out for criterion C3, frame construction time. For example, option S9 is ranked lower than all other options. Zero is inserted at the intersection of these options with option S9. Option S2 scores better than all other options. The number 1 is now inserted at its intersection with these options. The process is continued until all the concordance scores are established. Refer to Table 7.3.8.

Table 7.3.8: Criterion C3 – Frame construction time Concordance matrix (Dublin)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)
(S1)	1	0	1	1	1	1	1	1	1	1
(S2)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
(S3)	1	0	1	1	1	1	1	1	1	1
(S4)	1	0	1	1	1	1	1	1	1	1
(S5)	1	0	1	1	1	1	1	1	1	1
(S6)	1	0	1	1	1	1	1	1	1	1
(S7)	0	0	0	0	0	0	1	0	1	0
(S8)	0	0	0	0	0	0	1	1	1	1
(S9)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**
(S10)	0	0	0	0	0	0	1	1	1	1

The concordance scores above are now multiplied by the normalised weighting assigned to the criterion C3 by decision maker DM8. Reference to Table 7.3.1 shows this value to be 0.29. The scores along the rows and columns are added for each option as shown in Table 7.3.9

Table 7.3.9: Criterion C3 – Frame construction time Weighted matrix (Dublin) DM8

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	0.29	0	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	***2.61***
(S2)	**0.29**	**0.29**	**0.29**	**0.29**	**0.29**	**0.29**	**0.29**	**0.29**	**0.29**	**0.29**	***2.90***
(S3)	0.29	0	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	***2.61***
(S4)	0.29	0	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	***2.61***
(S5)	0.29	0	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	***2.61***
(S6)	0.29	0	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	***2.61***
(S7)	0	0	0	0	0	0	0.29	0	0.29	0	***0.58***
(S8)	0	0	0	0	0	0	0.29	0.29	0.29	0.29	***1.16***
(S9)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.29**	**0**	***0.29***
(S10)	0	0	0	0	0	0	0.29	0.29	0.29	0.29	***1.16***
Total	***1.74***	***0.29***	***1.74***	***1.74***	***1.74***	***1.74***	***2.61***	***2.32***	***2.90***	***2.32***	

The preferred option in terms of frame construction time is option S2 which has the highest row score and the lowest column score. The least preferred structural form is option S9 which has the lowest row score and the highest column score.

Finally, the procedure is carried out for criterion C4, overall construction time. For example, options S3, S5 and S6 are ranked lower than options S1, S2 and S4. Zero is inserted at the intersection of these options with option S3, S5 and S6. Options S3, S5 and S6 are ranked higher than options S7, S8, S9 and S10. The number 1 is inserted at the intersection of these options. The process is continued until all the concordance scores are established. Refer to Table 7.3.10.

Table 7.3.10: Criterion C4 – Overall construction time Concordance matrix (Dublin)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)
(S1)	1	0	1	1	1	1	1	1	1	1
(S2)	1	1	1	1	1	1	1	1	1	1
(S3)	**0**	**0**	**1**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
(S4)	1	0	1	1	1	1	1	1	1	1
(S5)	**0**	**0**	**1**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
(S6)	**0**	**0**	**1**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
(S7)	0	0	0	0	0	0	1	0	1	0
(S8)	0	0	0	0	0	0	1	1	1	0
(S9)	0	0	0	0	0	0	0	0	1	0
(S10)	0	0	0	0	0		1	1	1	1

The concordance scores above are now multiplied by the normalised weighting assigned to the criterion C4 by decision maker DM8. Reference to Table 7.3.1 shows this value to be 0.24. The scores along the rows and columns are added for each option as shown in Table 7.3.11.

Table 7.3.11: Criterion C4 – Overall construction time Weighted matrix (Dublin) DM8

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	0.24	0	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	***2.16***
(S2)	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	***2.40***
(S3)	**0**	**0**	**0.24**	**0**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	***1.68***
(S4)	0.24	0	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	***2.16***
(S5)	**0**	**0**	**0.24**	**0**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	***1.68***
(S6)	**0**	**0**	**0.24**	**0**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	***1.68***
(S7)	0	0	0	0	0	0	0.24	0	0.24	0	***0.48***
(S8)	0	0	0	0	0	0	0.24	0.24	0.24	0	***0.72***
(S9)	0	0	0	0	0	0	0	0	0.24	0	***0.24***
(S10)	0	0	0	0	0	0	0.24	0.24	0.24	0.24	***0.96***
Total	***0.72***	***0.24***	***1.44***	***0.72***	***1.44***	***1.44***	***2.16***	***1.92***	***2.40***	***1.68***	

The preferred option in terms of overall construction time is option S2 which has the highest row score and the lowest column score. The least preferred structural form is option S9 which has the lowest row score and the highest column score.

While the preferred and least preferred structural alternatives are evident for the four criteria on their own it is now required to combine this information and select the optimum solution based on cost, initial embodied energy, frame construction time and overall construction time. The overall weighted matrix is formed by adding the concordance scores of the individual weighted matrices. The sum of the rows and the sum of the columns are established for each decision maker. This is a crucial step in the application of multi-criteria analysis. 'Weights' used are simply a measure of the relative importance of the criteria involved. This is presented in Table 7.3.12.

Promethee 1 uses this property by taking each option's row score and ranking each option, placing the one with the highest score first, the one with the next highest score second, and so on until all are ranked. The method then takes the column scores and places the option with the highest score last, the one with the next highest score second last, and so on. A final ranking is obtained by finding the intersection between these two separate rankings. This is done by subtracting the column score of each option from its corresponding row score. The option with the highest score is considered the optimum solution.

Table 7.3.12: Overall performance matrix for all criteria (Dublin) DM8

	(S1)	**(S2)**	**(S3)**	**(S4)**	**(S5)**	**(S6)**	**(S7)**	**(S8)**	**(S9)**	**(S10)**	**Total**
(S1)	1.00	0.47	1.00	0.88	1.00	1.00	1.00	1.00	1.00	1.00	***9.35***
(S2)	0.53	1.00	0.53	0.53	0.88	0.88	1.00	1.00	1.00	1.00	***8.35***
(S3)	0.29	0.47	1.00	0.29	0.88	1.00	1.00	1.00	1.00	1.00	***7.93***
(S4)	0.65	0.47	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	***9.12***
(S5)	0.29	0.12	0.65	0.29	1.00	1.00	1.00	1.00	1.00	1.00	***7.35***
(S6)	0.29	0.12	0.53	0.29	0.53	1.00	1.00	1.00	1.00	1.00	***6.76***
(S7)	0	0	0	0	0	0	1.00	0	0.88	0	***1.88***
(S8)	0	0	0	0	0	0	1.00	1.00	1.00	0.29	***3.29***
(S9)	0	0	0	0	0	0	0.12	0	1.00	0	***1.12***
(S10)	0	0	0	0	0	0	1.00	1.00	1.00	1.00	***4.00***
Total	***3.05***	***2.65***	***4.71***	***3.28***	***5.29***	***5.88***	***9.12***	***8.00***	***9.88***	***7.29***	

S1 (9.35 – 3.05)	=	6.30	**S2** (8.35 – 2.65)	=	5.70
S3 (7.93 – 4.71)	=	3.22	**S4** (9.12 – 3.28)	=	5.84
S5 (7.35 – 5.29)	=	2.06	**S6** (6.76 – 5.88)	=	0.88
S7 (1.88 – 9.12)	=	-7.24	**S8** (3.29 – 8.00)	=	-4.71
S9 (1.12 – 9.88)	=	-8.76	**S10** (4.00 – 7.29)	=	-3.29

The ranking of the options, by decision maker DM8, using the Promothee 1 method is set out below:

1st **Option S1** (Slimflor® beams and pre-cast hollow core slab)
2nd **Option S4** (Composite beams and composite floor slab)
3rd **Option S2** (Slimflor® beams and deep deck floor un-propped)
4th **Option S3** (Slimflor® beams and deep deck floor propped)
5th **Option S5** (Cellular beams or castellated beams and composite slab)
6th **Option S6** (Composite beams with web openings)
7th **Option S10** (Precast double T units on reinforced concrete edge beams)
8th **Option S8** (Pre-cast hollow core units on R.C. edge beams)
9th **Option S7** (Reinforced concrete flat slab)
10th **Option S9** (Reinforced concrete waffle slab)

This exercise is carried out by the twenty one decision makers in relation to the ten structural options and four criteria in Dublin and Manchester. The ranking of the structural alternatives based on cost, initial embodied energy, frame construction time and overall construction does not change until the weightings are applied by the decision makers and the overall weighted matrix or performance matrix, for each decision maker, established. The ranking of the structural forms depends therefore on the 'weights' used. These are an indication of the measure of the relative importance of the criteria involved by the decision maker.

Results for Dublin

Figure 7.3.1 gives a graphical representation of the results obtained from the twenty one decision makers for Dublin.

Option S1, slimflor® beams and pre-cast hollow core slab, is selected as the optimum structural solution by eighteen of the decision makers. Option S2, composite beams and composite floor slab, is considered the preferred structural alternative by only three of the decision makers, two of whom place option S1 in second place. Option S2 is regarded as the third preferred solution by eighteen of the stakeholders, while option S4, slimflor® beams and deep deck floor propped, is ranked second by sixteen of the decision makers.

The diagram also shows that none of the concrete structural alternatives rank higher than seventh place and that all twenty one decision makers give the same ranking to each. Option S10, reinforced concrete waffle slab, is the preferred concrete building form while option S9 is ranked the lowest of the ten structural solutions.

The results make the decision process in Dublin conclusive as there is no ambiguity over the optimum structure.

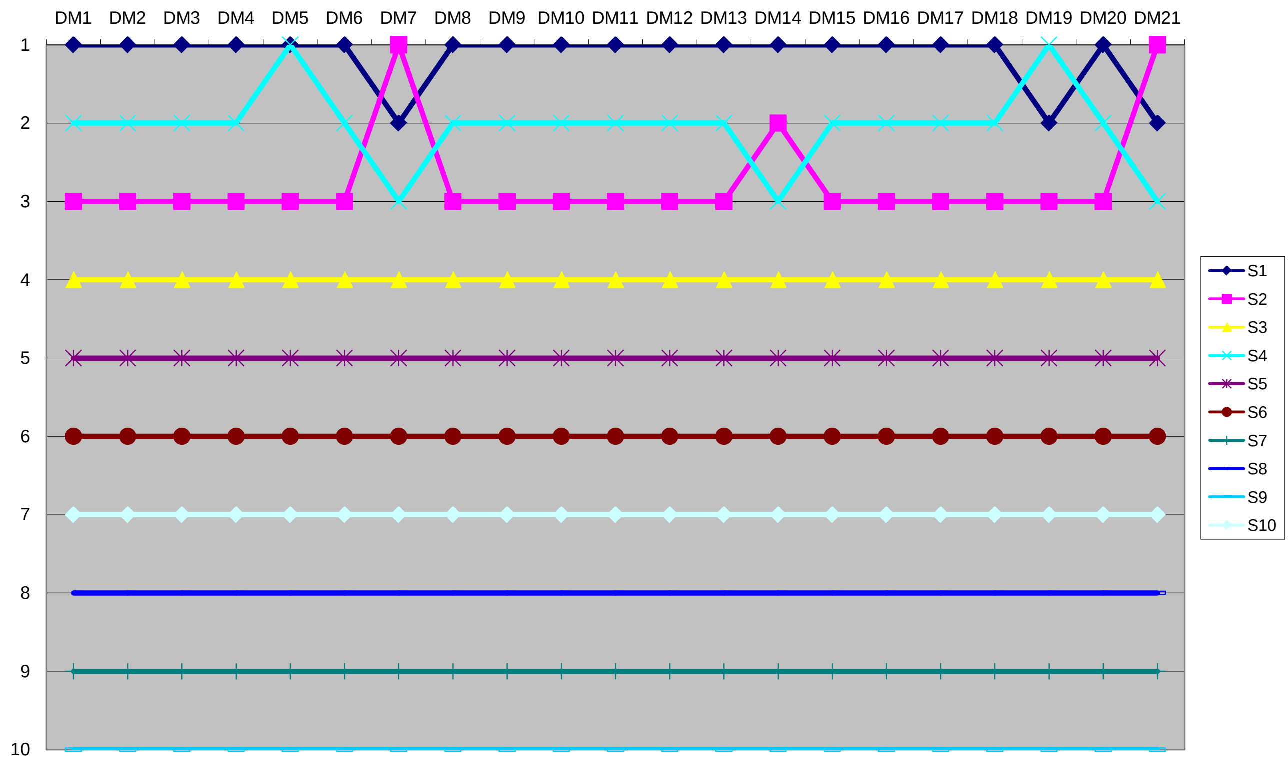

Figure 7.3.1: Promothee 1 results for all 21 decision makers (Dublin)

Reference to Figure 7.3.1 shows the ranking of the options in Dublin by the twenty one decision makers, using the Promothee 1 method:

1st **Option S1** (Slimflor® beams and pre-cast hollow core slab)
2nd **Option S4** (Composite beams and composite floor slab)
3rd **Option S2** (Slimflor® beams and deep deck floor un-propped)
4th **Option S3** (Slimflor® beams and deep deck floor propped)
5th **Option S5** (Cellular beams or castellated beams and composite slab)
6th **Option S6** (Composite beams with web openings)
7th **Option S10** (Precast double T units on reinforced concrete edge beams)
8th **Option S8** (Pre-cast hollow core units on R.C. edge beams)
9th **Option S7** (Reinforced concrete flat slab)
10th **Option S9** (Reinforced concrete waffle slab)

Results for Manchester

On the basis of both the derived rankings and the importance weightings assigned to each criterion by the decision makers, a set of concordance indices for each pair of options on each of the four decision criteria is compiled. This is done for each of the twenty one decision makers in Manchester.

The concordance, weighted and overall performance matrices for each of the four criteria for Decision Maker DM8 are set out in Appendix B.

Figure 7.3.2 gives a graphical representation of the results obtained from the twenty one decision makers for Manchester.

Option S2, slimflor® beams and deep deck floor un-propped is selected as the optimum structural solution by twenty of the decision makers. In contrast to Dublin, option S1, slimflor® beams and pre-cast hollow core slab, is considered the preferred solution by only one of the decision makers. Option S1 and option S4, composite beams and composite floor slab, are ranked very close in second and third place respectively. It would be difficult to decide which of these options are more preferable.

In the same way, it would be difficult to make a decision between option S3, slimflor® beams and deep deck floor propped, and option S5, composite beams with web openings. Eight decision makers rank option S3 and option S5 in fourth and fifth position respectively, while eleven stakeholders rank the same options in fifth and fourth place respectively. Only two of the decision makers select option S5 as their second preferred structural alternative thus giving this option a slight lead over option S3.

Similar to the results in Dublin, the concrete structural solutions are ranked below the steel structural forms with option S8, pre-cast hollow core units on R.C. edge beams, ranked as the preferred concrete option and option S9, reinforced concrete waffle slab, considered the least preferred concrete alternative.

Option S7, reinforced concrete flat slab, and option S8 are so closely ranked that it is almost impossible to select one as the more suitable form. Ten decision makers place both options in 7th place, while eight stakeholders rank option S7 in eighth position and nine stakeholders rank option S8 in eighth position.

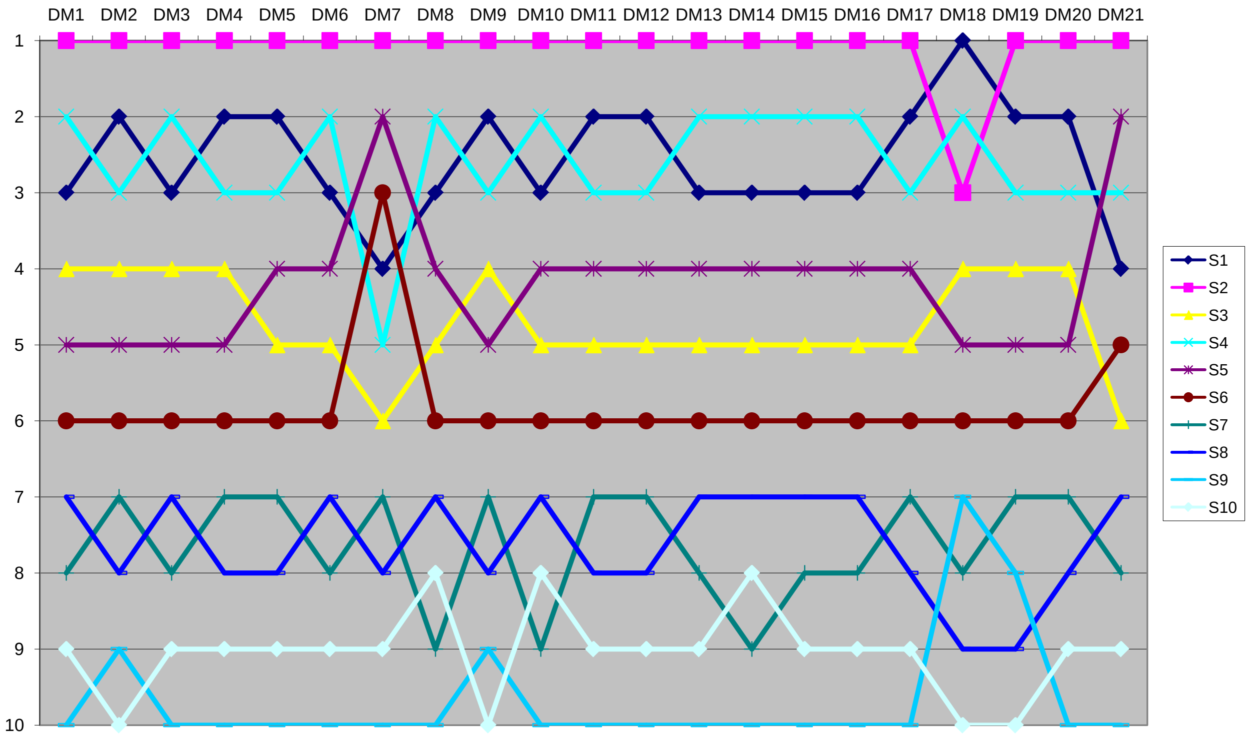

Figure 7.3.2: Promethee 1 results for all 21 decision makers (Manchester)

Reference to Figure 7.3.2 shows the ranking of the options in Manchester by the twenty one decision makers, using the Promothee 1 method:

1st **Option S2** (Slimflor℗ beams and deep deck floor un-propped)

2nd **Option S1** (Slimflor℗ beams and pre-cast hollow core slab)

3rd **Option S4** (Composite beams and composite floor slab)

4th **Option S5** (Cellular beams or castellated beams and composite slab)

5th **Option S3** (Slimflor℗ beams and deep deck floor propped)

6th **Option S6** (Composite beams with web openings)

7th **Option S8** (Pre-cast hollow core units on R.C. edge beams)

8th **Option S7** (Reinforced concrete flat slab)

9th **Option S10** (Precast double T units on reinforced concrete edge beams)

10th **Option S9** (Reinforced concrete waffle slab)

Mean, Median and Mode

It is also useful to consider the mean, median and mode of the weightings by the twenty one decision makers and apply the normalised weights to each of the criteria matrices to form an overall weighted matrix and thus determine if the ranking of options remains as shown above for both locations. This strengthens the information compiled from the stakeholders. In this study the values are represented by the weightings applied to the four criteria by the twenty one decision makers. The initial step in calculating the mean, median and mode is set out in Table 7.3.13.

Using the same concordance matrices as for the twenty one decision makers the weighted matrix for each of the criteria is established. Tables 7.3.14 to 7.3.19 show the mean, median and mode performance matrices for Dublin and Manchester.

Table 7.3.13: Weighting applied by the Decision Makers

Decision Makers	Cost C1	Embodied Energy C2	Frame Const. C3	Overall Const. C4	Total
DM1	7	3	3	5	18
DM2	7	5	5	6	23
DM3	7	3	4	5	19
DM4	7	4	7	5	23
DM5	5	5	6	7	23
DM6	7	3	5.5	5.5	21
DM7	3	2	5	7	17
DM8	6	2	5	4	17
DM9	6	4	4	5	19
DM10	6	1	3	4	14
DM11	6	3.5	6	6	21.5
DM12	7	4	7	6	24
DM13	5	2	4	5	16
DM14	7	1	4	5	17
DM15	5	2	4	5	16
DM16	7	3	5	7	22
DM17	5	4	5	7	21
DM18	5	3	2	2	12
DM19	5	7	5	6	23
DM20	7	4	6	4	21
DM21	5	2	5	7	19
Total	125.00	67.50	100.50	113.50	406.50
Mean	125.00/21 (5.952)	67.50/21 (3.214)	100.50/21 (4.786)	113.50/21 (5.405)	406.50/21 (19.357)
Median	6	3	5	5	19
Mode	7	3	5	5	20

Table 7.3.14: Mean matrix for all criteria (Dublin)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	1.00	0.47	1.00	0.83	1.00	1.00	1.00	1.00	1.00	1.00	***9.30***
(S2)	0.53	1.00	0.53	0.53	0.83	0.83	1.00	1.00	1.00	1.00	***8.25***
(S3)	0.25	0.47	1.00	0.25	0.83	1.00	1.00	1.00	1.00	1.00	***7.80***
(S4)	0.69	0.47	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	***9.16***
(S5)	0.25	0.17	0.69	0.25	1.00	1.00	1.00	1.00	1.00	1.00	***7.36***
(S6)	0.25	0.17	0.53	0.25	0.53	1.00	1.00	1.00	1.00	1.00	***6.73***
(S7)	0	0	0	0	0	0	1.00	0	0.83	0	***1.83***
(S8)	0	0	0	0	0	0	1.00	1.00	1.00	0.25	***3.25***
(S9)	0	0	0	0	0	0	0.16	0	1.00	0	***1.16***
(S10)	0	0	0	0	0	0	1.00	1.00	1.00	1.00	***4.00***
Total	***2.97***	***2.75***	***4.75***	***3.11***	***5.19***	***5.83***	***9.16***	***8.00***	***9.83***	***7.25***	

S1	(9.30 – 2.97)	=	6.33
S4	(9.16 – 3.11)	=	6.05
S2	(8.25 – 2.75)	=	5.50
S3	(7.80 – 4.75)	=	3.05
S5	(7.36 – 5.19)	=	2.17
S6	(6.73 – 5.83)	=	0.90
S10	(4.00 – 7.25)	=	-3.25
S8	(3.25 – 8.00)	=	-4.75
S7	(1.83 – 9.16)	=	-8.33
S9	(1.16 – 9.83)	=	-8.67

Table 7.3.15: Median matrix for all criteria (Dublin)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	1.00	0.47	1.00	0.84	1.00	1.00	1.00	1.00	1.00	1.00	***9.31***
(S2)	0.53	1.00	0.53	0.53	0.84	0.84	1.00	1.00	1.00	1.00	***8.27***
(S3)	0.26	0.47	1.00	0.26	0.84	1.00	1.00	1.00	1.00	1.00	***7.83***
(S4)	0.68	0.47	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	***9.15***
(S5)	0.26	0.16	0.68	0.26	1.00	1.00	1.00	1.00	1.00	1.00	***7.36***
(S6)	0.26	0.16	0.53	0.26	0.53	1.00	1.00	1.00	1.00	1.00	***6.74***
(S7)	0	0	0	0	0	0	1.00	0	0.84	0	***1.84***
(S8)	0	0	0	0	0	0	1.00	1.00	1.00	0.26	***3.26***
(S9)	0	0	0	0	0	0	0.16	0	1.00	0	***1.16***
(S10)	0	0	0	0	0	0	1.00	1.00	1.00	1.00	***4.00***
Total	***2.99***	***2.73***	***4.74***	***3.15***	***5.21***	***5.84***	***9.16***	***8.00***	***9.84***	***7.26***	

S1	(9.31 – 2.99)	=	6.32
S4	(9.15 – 3.15)	=	6.00
S2	(8.27 – 2.73)	=	5.54
S3	(7.83 – 4.74)	=	3.09
S5	(7.36 – 5.21)	=	2.15
S6	(6.74 – 5.84)	=	0.90
S10	(4.00 – 7.26)	=	-3.26
S8	(3.26 – 8.00)	=	-4.74
S7	(1.84 – 9.16)	=	-7.32
S9	(1.16 – 9.84)	=	-8.68

Table 7.3.16: Mode matrix for all criteria (Dublin)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	1.00	0.50	1.00	0.85	1.00	1.00	1.00	1.00	1.00	1.00	***9.35***
(S2)	0.50	1.00	0.50	0.50	0.85	0.85	1.00	1.00	1.00	1.00	***8.20***
(S3)	0.25	0.50	1.00	0.25	0.85	1.00	1.00	1.00	1.00	1.00	***7.85***
(S4)	0.65	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	***9.15***
(S5)	0.25	0.15	0.65	0.25	1.00	1.00	1.00	1.00	1.00	1.00	***7.30***
(S6)	0.25	0.15	0.50	0.25	0.50	1.00	1.00	1.00	1.00	1.00	***6.65***
(S7)	0	0	0	0	0	0	1.00	0	0.85	0	***1.85***
(S8)	0	0	0	0	0	0	1.00	1.00	1.00	0.25	***3.25***
(S9)	0	0	0	0	0	0	0.15	0	1.00	0	***1.15***
(S10)	0	0	0	0	0	0	1.00	1.00	1.00	1.00	***4.00***
Total	***2.90***	***2.80***	***4.65***	***3.10***	***5.20***	***5.85***	***9.15***	***8.00***	***9.85***	***7.25***	

S1	(9.35 – 2.90)	=	6.45
S4	(9.15 – 3.10)	=	6.05
S2	(8.20 – 2.80)	=	5.40
S3	(7.85 – 4.65)	=	3.20
S5	(7.30 – 5.20)	=	2.10
S6	(6.65 – 5.85)	=	0.80
S10	(4.00 – 7.25)	=	-3.25
S8	(3.25 – 8.00)	=	-4.75
S7	(1.85 – 9.15)	=	-7.30
S9	(1.15 – 9.85)	=	-8.70

Table 7.3.17: Mean matrix for all criteria (Manchester)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	1.00	0.474	1.00	0.692	0.474	0.474	0.834	1.00	0.834	1.00	***7.782***
(S2)	0.526	1.0	0.526	0.526	1.00	1.00	0.834	1.00	0.834	1.00	***8.246***
(S3)	0.526	0.474	1.00	0.692	0.474	0.474	0.834	1.00	0.834	1.00	***7.308***
(S4)	0.834	0.474	0.834	1.00	0.474	0.474	0.834	1.00	0.834	1.00	***7.758***
(S5)	0.526	0.247	0.526	0.526	1.00	1.00	0.834	0.834	0.834	0.834	***7.161***
(S6)	0.526	0.247	0.526	0.526	0.526	1.00	0.834	0.834	0.834	0.834	***6.687***
(S7)	0.166	0.166	0.166	0.166	0.166	0.166	1.00	0.692	0.526	0.692	***3.906***
(S8)	0	0	0	0	0.166	0.166	0.834	1.00	0.834	1.00	***4.00***
(S9)	0.166	0.166	0.166	0.166	0.166	0.166	0.474	0.166	1.00	0.166	***2.802***
(S10)	0	0	0	0	0.166	0.166	0.834	0.692	0.834	1.00	***3.692***
Total	***4.27***	***3.248***	***4.744***	***4.294***	***4.612***	***5.086***	***8.146***	***8.218***	***8.198***	***8.526***	

S2	(8.246 – 3.248)	=	4.998
S1	(7.782 – 4.270)	=	3.512
S4	(7.758 – 4.294)	=	3.464
S3	(7.308 – 4.744)	=	2.564
S5	(7.161 – 4.612)	=	2.549
S6	(6.687 – 5.086)	=	1.601
S8	(4.000 – 8.218)	=	-4.218
S7	(3.906 – 8.146)	=	-4.240
S10	(3.692 – 8.526)	=	-4.834
S9	(2.803 – 8.198)	=	-5.395

Table 7.3.18: Median matrix for all criteria (Manchester)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	1.00	0.47	1.00	0.68	0.47	0.47	0.84	1.00	0.84	1.00	***7.77***
(S2)	0.53	1.0	0.53	0.53	1.00	1.00	0.84	1.00	0.84	1.00	***8.27***
(S3)	0.53	0.47	1.00	0.68	0.47	0.47	0.84	1.00	0.84	1.00	***7.30***
(S4)	0.84	0.47	0.84	1.00	0.47	0.47	0.84	1.00	0.84	1.00	***7.77***
(S5)	0.53	0.26	0.53	0.53	1.00	1.00	0.84	0.84	0.84	0.84	***7.21***
(S6)	0.53	0.26	0.53	0.53	0.53	1.00	0.84	0.84	0.84	0.84	***6.74***
(S7)	0.16	0.16	0.16	0.16	0.16	0.16	1.00	0.68	0.53	0.68	***3.85***
(S8)	0	0	0	0	0.16	0.16	0.84	1.00	0.84	1.00	***4.00***
(S9)	0.16	0.16	0.16	0.16	0.16	0.16	0.48	0.16	1.00	0.16	***2.76***
(S10)	0	0	0	0	0.16	0.16	0.84	0.68	0.84	1.00	***3.68***
Total	***4.27***	***3.25***	***4.75***	***4.27***	***4.58***	***5.05***	***8.20***	***8.20***	***8.25***	***8.52***	

S2	(8.27 – 3.25)	=	5.02
S1	(7.77 – 4.27)	=	3.50
S4	(7.77 – 4.27)	=	3.50
S5	(7.21 – 4.58)	=	2.63
S3	(7.30 – 4.75)	=	2.55
S6	(6.74 – 5.05)	=	1.69
S8	(4.00 – 8.20)	=	-4.20
S7	(3.85 – 8.20)	=	-4.35
S10	(3.68 – 8.52)	=	-4.84
S9	(2.76 – 8.25)	=	-5.49

Table 7.3.19: Mode matrix for all criteria (Manchester)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	1.00	0.50	1.00	0.65	0.50	0.50	0.85	1.00	0.85	1.00	***7.85***
(S2)	0.5	1.0	0.50	0.50	1.00	1.00	0.85	1.00	0.85	1.00	***8.20***
(S3)	0.50	0.50	1.00	0.65	0.50	0.50	0.85	1.00	0.85	1.00	***7.35***
(S4)	0.85	0.50	0.85	1.00	0.50	0.50	0.85	1.00	0.85	1.00	***7.90***
(S5)	0.50	0.25	0.5	0.50	1.00	1.00	0.85	0.85	0.85	0.85	***7.15***
(S6)	0.50	0.25	0.5	0.50	0.50	1.00	0.85	0.85	0.85	0.85	***6.65***
(S7)	0.15	0.15	0.15	0.15	0.15	0.15	1.00	0.65	0.50	0.65	***3.70***
(S8)	0	0	0	0	0.15	0.15	0.85	1.00	0.85	1.00	***4.00***
(S9)	0.15	0.15	0.15	0.15	0.15	0.15	0.50	0.15	1.00	0.15	***2.70***
(S10)	0	0	0	0	0.15	0.15	0.85	0.65	0.85	1.00	***3.65***
Total	***4.15***	***3.30***	***4.65***	***4.10***	***4.60***	***5.10***	***8.30***	***8.15***	***8.30***	***8.50***	

S2 (8.20 – 3.30) = 4.90

S4 (7.90 – 4.10) = 3.80

S1 (7.85 – 4.15) = 3.70

S3 (7.35 – 4.65) = 2.70

S5 (7.15 – 4.60) = 2.55

S6 (6.65 – 5.10) = 1.55

S8 (4.00 – 8.15) = -4.15

S7 (3.70 – 8.30) = -4.60

S10 (3.65 – 8.50) = -4.85

S9 (2.70 – 8.30) = -5.6

The mean, median and mode are presented in Figure 7.3.3 for Dublin and Figure 7.3.4 for Manchester.

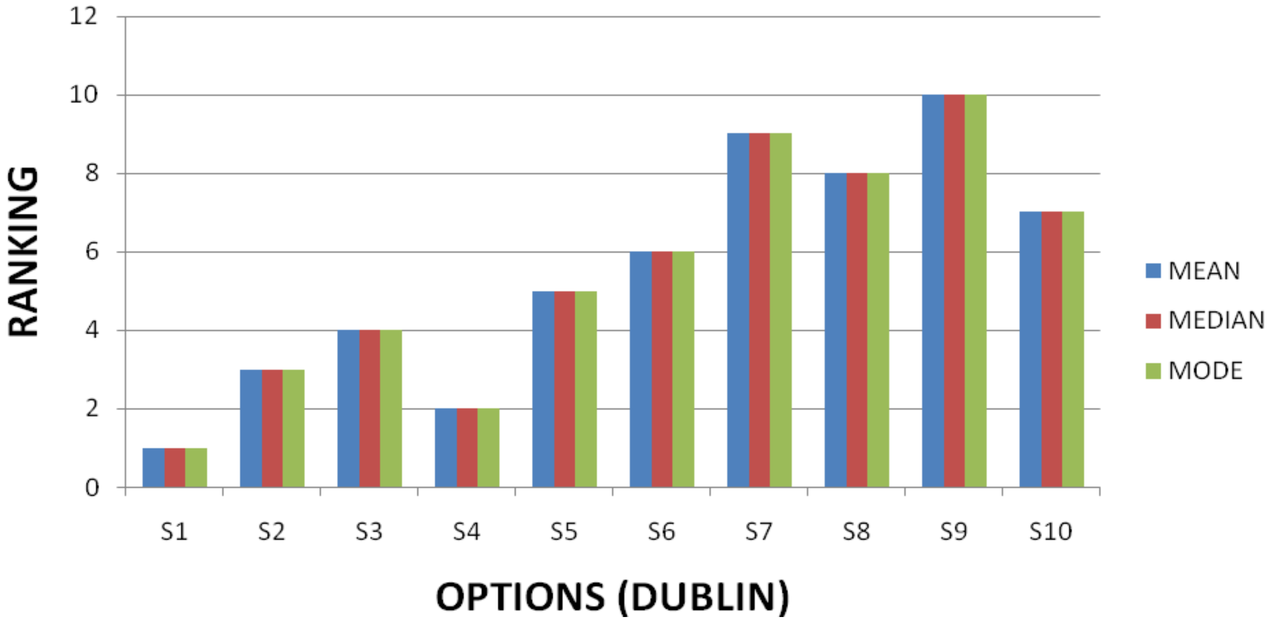

Figure 7.3.3: Mean, median and mode – Promothee 1 (Dublin)

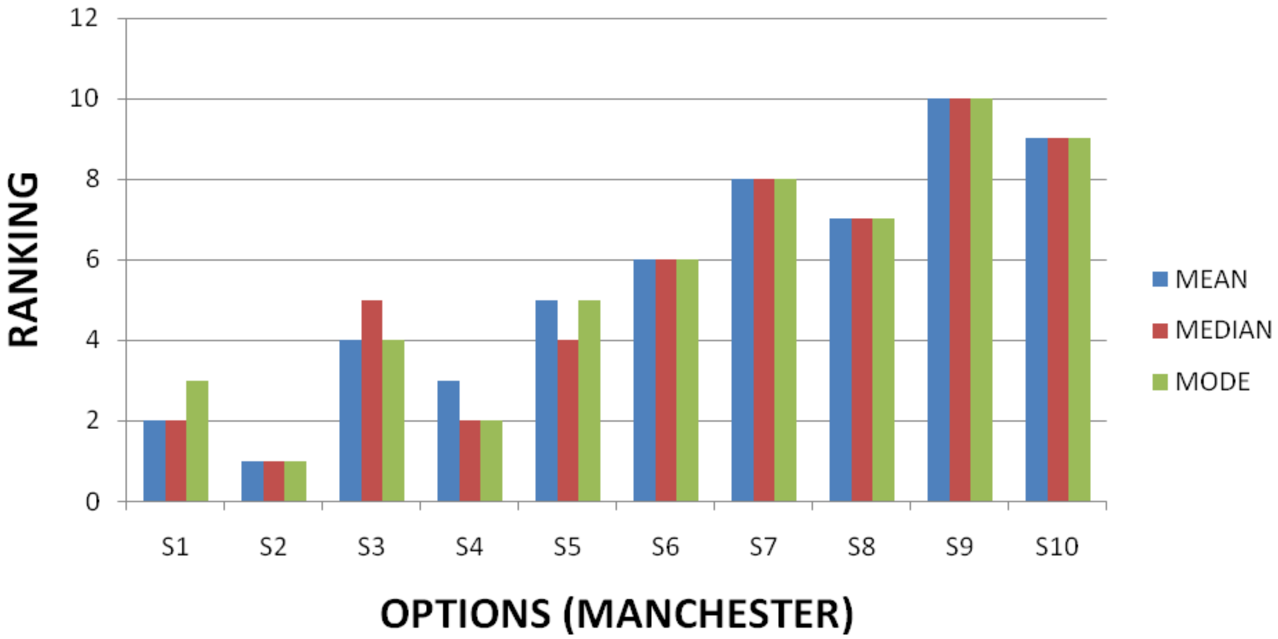

Figure 7.3.4: Mean, median and mode – Promothee 1 (Manchester)

The ranking of the structural options for Dublin remains the same for the mean, median and mode and for the twenty one decision makers. This makes the selection of the optimum structural form very straightforward. However, the results for Manchester are more diverse. The decision makers, mean and median rank option S1, slimflor® beams and pre-cast hollow core slab in second place, while the mode ranks it in third position. In all cases option S2, slimflor® beams and deep deck floor un-propped, is the preferred solution. Option S4, composite beams and composite floor slab, is ranked third by the decision makers and the mean while the median and mode place it in second position. Option S3, slimflor® beams and deep deck floor propped, and option S5, cellular beams or castellated beams and composite slab, share fourth and fifth position.

In both locations, the concrete options rank below the steel structural forms for the twenty one stakeholders, mean, median and mode. Option S10, precast double T units on reinforced concrete edge beams, remains the favoured concrete alternative in Dublin for the decision makers, mean, median and mode. Option S8, pre-cast hollow core units on R.C. edge beams, is the optimum concrete structural form for the stakeholders, mean, median and mode in Manchester. Option S9, reinforced concrete waffle slab, is regarded as the least preferred option in all cases for both locations.

The ranking results of the decision makers, mean median and mode for Dublin and Manchester are presented in Table 7.3.20

Table 7.3.20: Summary of ranking using Promethee 1

Structural Option	Dublin				Manchester			
	DM	Mean	Median	Mode	DM	Mean	Median	Mode
S1	1st	1st	1st	1st	2nd	2nd	2nd	3rd
S2	3rd	3rd	3rd	3rd	1st	1st	1st	1st
S3	4th	4th	4th	4th	5th	4th	5th	4th
S4	2nd	2nd	2nd	2nd	3rd	3rd	2nd	2nd
S5	5th	5th	5th	5th	4th	5th	4th	5th
S6	6th	6th	6th	6th	6th	6th	6th	6th
S7	9th	9th	9th	9th	8th	8th	8th	8th
S8	8th	8th	8th	8th	7th	7th	7th	7th
S9	10th	10th	10th	10th	10th	10th	10th	10th
S10	7th	7th	7th	7th	9th	9th	9th	9th

8 Conclusion

Over the 1994 to 2004 period, the Steel Construction Institute in the UK produced a study which compared 10 structural forms on the basis of cost, initial embodied energy, frame construction time and overall construction time. A generic open plan commercial building, located in Manchester, was used for this study, with the form of the building chosen to draw out the most important differences between the structural systems examined.

The thesis has estimated the cost, initial embodied energy, frame construction time and overall construction time of the 10 structural forms of this generic building in Dublin and ranked the 10 options on the basis of cost, initial embodied energy, frame construction time and overall construction time. Then, using multi-criteria analysis, has produced a ranking of all forms on the basis of their performance on all 4 criteria. The multi-criteria analysis was completed in two stages. In the first, two relatively simple models, 'dominance' and 'Borda Sum-Of-Ranks', enabled the better performing options to be distinguished from the less well performing ones, with the more complex 'Promethee 1' model used to generate a full ranking of all options examined.

The 1994 and 2004 UK analysis compared the structural forms on the basis of cost, initial embodied energy, frame construction time and overall construction time, but did not utilise any formal model to derive a ranking of the 10 forms examined. This study repeats the modelling process for the Manchester data in order to derive a complete ranking on the basis of the 4 criteria so that these results can be compared with the Dublin data compiled in this thesis.

A comparison of the results from the multi-criteria decision analysis of the ten steel and concrete framed structures using the Borda, Dominance and Promethee 1 methods, with regard to the four criteria, are presented graphically in Figure 8.1 for Dublin and Figure 8.2 for Manchester. Tables 8.1 and 8.2 present the values applied to each of the four criteria for the ten structural forms in Dublin and Manchester respectively.

Taking the Dublin data, option S1, slimflor® beams and pre-cast hollow core slab, is the preferred structural form on the basis of cost only, followed by option S4, composite beams and composite floor slab, option S3, slimflor® beams and deep deck floor propped and option S2, , slimflor® beams and deep deck floor un-propped. All other options are a minimum of just less than 20% more expensive than option S1.

Comparing the structural forms on the basis of all four criteria, the preliminary Dominance Model indicates three options, S1, S2 and S4, are not 'dominated by any of the other structural forms and are thus identified as among the better performing options. The simple Borda Sum-Of-Ranks model confirms options S1 and S4 performing well across all four criteria.

The Promethee 1 Model requires not only the performance of all 10 forms on each of the 4 criteria, but also requires information of the relative importance of the weightings to the relevant decision makers.

The study derived relative importance scores for the 4 criteria from 21 decision makers involved in the construction process. The group comprised structural engineers, architects, quantity surveyors, planners and developers/contractors. A final ranking of the 10 structural forms was thus derived for each of the 21 decision makers.

The rankings derived from the Promethee 1 Model confirms S1 to be the best performing option for 17 of the 21 decision makers, with S4 ranked second with 17 out of 21 decision makers (and ranked first on 2) and S2 ranked third for 18 out of 21 decision makers (and ranked first on 2).

This order is based on S1 being the best performing option on cost and the second best performing option on the remaining criteria. S2 ranks second on one option, fourth on one and third on the remaining two, while S3 is ranked first on two of the criteria but ranks fourth and sixth on the other two. It is thus self evident that option S1 is the most consistently performing form of the 10 examined.

Based on the data gathered by the Steel Construction Institute (1994, 2004) for the generic building assumed to be located in Manchester, option S4, Composite beams and composite floor slab, is the preferred structural form on the basis of cost only, followed by option S1, slimflor® beams and pre-cast hollow core slab, option S3, slimflor® beams and deep deck floor propped and option S2, slimflor® beams and deep deck floor un-propped. All other options are a minimum of just less than 15% more expensive than option S4.

Comparing the structural forms on the basis of all four criteria, the preliminary Dominance Model indicates five options, S1, S2, S4, S7 and S9, are not 'dominated by any of the other structural forms and are thus identified as among the better performing options. The simple Borda model confirms options S1, S2 and S4 performing well across all four criteria.

As use of the more sophisticated/complex Promethee 1 Model, which produces a full ranking of all structural forms considered, requires not only the performance of all 10 forms on each of the 4 criteria, but also information of the relative importance of the weightings to the relevant decision makers, the study has combined the criterion scores for all 10 Manchester-based options from the Steel Construction Institute with relative importance scores compiled by the study for the 4 criteria based on the responses of 21 Dublin-based stakeholders from within the Irish construction industry.

The rankings derived from the Promethee 1 Model indicates that S2 to be the best performing option for 20 of the 21 decision makers (and ranked third for 1), with S1 ranked second with 9 out of 21 decision makers (and ranked first on 1 and third on 9) and S4 ranked third for 10 out of 21 decision makers (and ranked first on 0 and second on 10). It can thus be seen that S1 and S4 are virtually indistinguishable in terms of their performance on the four criteria.

This order is based on S2 being the best performing option on both frame and overall construction time, while being ranked fourth and sixth on cost and initial embodied energy respectively. S1 ranks second on the basis of its consistent performance across the criteria, with one second (cost), one third (embodied energy) and two fourths (frame and overall construction time). S4 is ranked third on the basis that, while it is the cheapest option, it ranks only fourth on frame and overall construction time and fifth on embodied energy.

Thus, while both sets of data confirm that options S1, S2 and S4 as the best performing of the 10 options examined, Dublin places S1 and S4 in first and second, whereas Manchester places option S2 first. This is in contrast to the cost-only data, which places S1 first in both locations.

Thus, although there are some small differences between the relative cost of the ten options in Dublin and Manchester, the overall performance is similar, with the same three options performing best**.** However, some inconsistencies do occur when one examines the difference in performance of the various options at the two locations on the other criteria, particularly in initial embodied energy. As the measurement of this criterion is based on the mass and therefore the weight of the material it would be expected that the concrete options use more initial embodied energy than the steelwork alternatives. As discussed earlier within Chapter 4, it is stated that, although the energy intensity value for steelwork is significantly greater than for concrete, the large mass of concrete tends to negate its lower value of energy intensity, with the volume of concrete foundations for the concrete options being on average 60% greater than for the steel options.

In Dublin this is clearly reflected in the initial embodied energy values for production. However, in Manchester option 7 (reinforced concrete slab) and option 9 (reinforced concrete waffle slab) rank 2nd and 1st respectively on this criterion. This inconsistent outcome prompts questions with regard to how the embodied energy criterion for the 10 structural forms in Manchester was measured. (The strong performance of S7 and S9 on this criterion results these options performing well within the preliminary Dominance Model, even though their weak performance on the other two criteria result in an overall ranking of 8th and 10th respectively. This is a direct result of the relatively low importance weighting given to initial embodied energy by the 21 decision makers. Given the prominence at present given by designers to the sustainability of a building project, the low importance weighting assigned by decision makers to this criterion merits deeper examination**.**

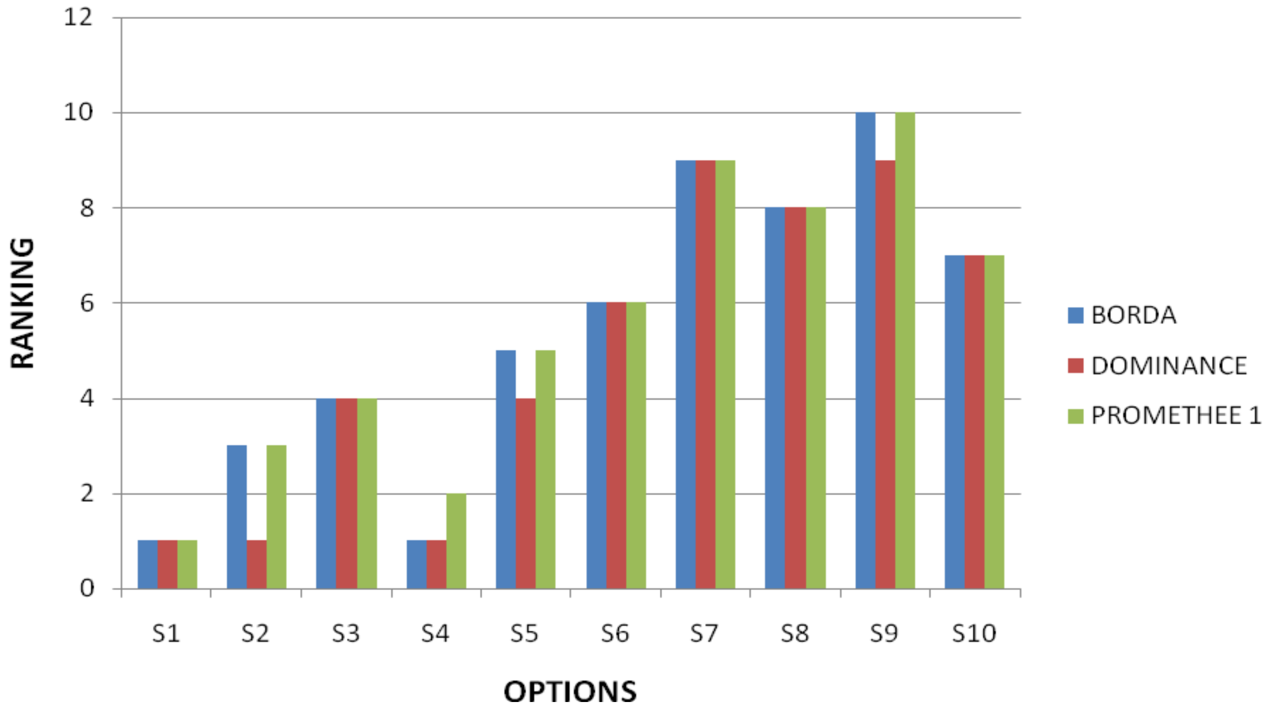

Figure 8.1: Comparison of Borda, Dominance and Promothee 1 (Dublin)

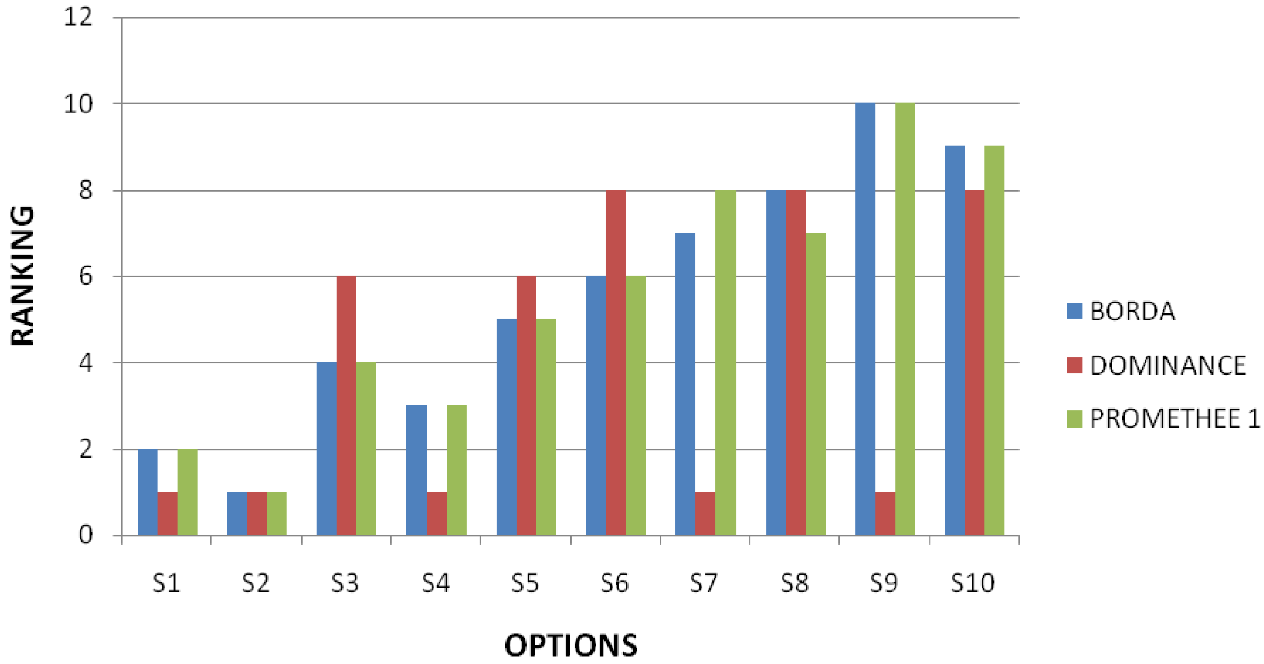

Figure 8.2: Comparison of Borda, Dominance and Promothee 1 (Manchester)

Table 8.1: Values assigned to the four criteria in Dublin.

Structural Option	Cost (euro/m^2)	Initial Embod. Energy Production Transportation Construction (GJ/m^2)	Frame Const. Time (weeks)	Overall Const. Time (weeks)
Option 1 Slimflor® beams and pre-cast hollowcore slab	319.82	3.89	7	41
Option 2 Slimflor® beams and deep deck floor (un-propped)	364.67	4.40	6	40
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	351.05	4.25	7	42
Option 4 Composite beams and floor slab	329.13	3.80	7	41
Option 5 Cellular beams or castillated beams and composite slab	380.11	4.18	7	42
Option 6 Composite beams with web openings	387.29	4.26	7	42
Option 7 Reinforced concrete flat slab	438.74	4.95	10	46
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	431.00	4.53	9	44
Option 9 Reinforced concrete waffle slab	443.30	4.71	12	48
Option 10 Pre-cast double T units on reinforced concrete edge beams	424.60	4.42	9	43

Table 8.2: Values assigned to the four criteria in Manchester.

Structural Option	Cost (£/m^2)	Initial Embod. Energy Production (GJ/m^2)	Frame Const. Time (weeks)	Overall Const. Time (weeks)
Option 1 Slimflor® beams and pre-cast hollowcore slab	236.87	2.63	7	42
Option 2 Slimflor® beams and deep deck floor (un-propped)	245.15	2.75	6	40
Option 3 Slimflor® beams and deep deck floor (propped 7.5m span)	244.03	2.65	7	42
Option 4 Composite beams and floor slab	226.12	2.70	7	42
Option 5 Cellular beams or castillated beams and composite slab	258.52	2.98	6	41
Option 6 Composite beams with web openings	264.58	3.12	6	41
Option 7 Reinforced concrete flat slab	292.32	2.50	8	43
Option 8 Pre-cast hollow core units on reinforced concrete edge beams	275.25	2.80	8	43
Option 9 Reinforced concrete waffle slab	291.10	2.48	13	50
Option 10 Pre-cast double T units on reinforced concrete edge beams	276.48	2.80	8	43

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Appendix A

Survey Results of the 21 Decision Makers

Decision Maker 1 - Engineer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	3
FRAME CONSTRUCTION TIME	3
TOTAL CONSTRUCTION TIME	5

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 2 - Engineer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	5
FRAME CONSTRUCTION TIME	5
TOTAL CONSTRUCTION TIME	6

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 3 - Academic

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	3
FRAME CONSTRUCTION TIME	4
TOTAL CONSTRUCTION TIME	5

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 4 – Quantity Surveyor

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	4
FRAME CONSTRUCTION TIME	7
TOTAL CONSTRUCTION TIME	5

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 5 - Developer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	5
TOTAL INITIAL EMBODIED ENERGY	5
FRAME CONSTRUCTION TIME	6
TOTAL CONSTRUCTION TIME	7

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 6 - Engineer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	3
FRAME CONSTRUCTION TIME	5-6
TOTAL CONSTRUCTION TIME	5-6

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 7 - Developer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	3
TOTAL INITIAL EMBODIED ENERGY	2
FRAME CONSTRUCTION TIME	5
TOTAL CONSTRUCTION TIME	7

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 8 - Engineer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	6
TOTAL INITIAL EMBODIED ENERGY	2
FRAME CONSTRUCTION TIME	5
TOTAL CONSTRUCTION TIME	4

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 9 - Architect

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	6
TOTAL INITIAL EMBODIED ENERGY	4
FRAME CONSTRUCTION TIME	4
TOTAL CONSTRUCTION TIME	5

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 10 – Quantity Surveyor

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	6
TOTAL INITIAL EMBODIED ENERGY	1
FRAME CONSTRUCTION TIME	3
TOTAL CONSTRUCTION TIME	4

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 11 - Developer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	6
TOTAL INITIAL EMBODIED ENERGY	3/4
FRAME CONSTRUCTION TIME	6
TOTAL CONSTRUCTION TIME	6

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 12 - Planner

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	4
FRAME CONSTRUCTION TIME	7
TOTAL CONSTRUCTION TIME	6

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 13 – Quantity Surveyor

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	5
TOTAL INITIAL EMBODIED ENERGY	2
FRAME CONSTRUCTION TIME	4
TOTAL CONSTRUCTION TIME	5

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 14 – Quantity Surveyor

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	1
FRAME CONSTRUCTION TIME	4
TOTAL CONSTRUCTION TIME	5

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 15 - Developer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	5
TOTAL INITIAL EMBODIED ENERGY	2
FRAME CONSTRUCTION TIME	4
TOTAL CONSTRUCTION TIME	5

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 16 - Engineer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	3
FRAME CONSTRUCTION TIME	5
TOTAL CONSTRUCTION TIME	7

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 17 - Architect

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	5
TOTAL INITIAL EMBODIED ENERGY	4
FRAME CONSTRUCTION TIME	5
TOTAL CONSTRUCTION TIME	7

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 18 - Planner

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	5
TOTAL INITIAL EMBODIED ENERGY	3
FRAME CONSTRUCTION TIME	2
TOTAL CONSTRUCTION TIME	2

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 19 - Academic

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	5
TOTAL INITIAL EMBODIED ENERGY	7
FRAME CONSTRUCTION TIME	5
TOTAL CONSTRUCTION TIME	6

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 20 - Architect

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	7
TOTAL INITIAL EMBODIED ENERGY	4
FRAME CONSTRUCTION TIME	6
TOTAL CONSTRUCTION TIME	4

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Decision Maker 21 - Developer

10 No. different forms of construction / structural options (steel, reinforced concrete, pre-stressed concrete, composite) are being compared based on their performance on the following 4 criteria:

- TOTAL STRUCTURAL COST
- TOTAL INITIAL EMBODIED ENERGY (energy used in material production, transportation and construction on site)
- FRAME CONSTRUCTION TIME
- TOTAL CONSTRUCTION TIME

Please score these criteria from 1 to 7 with 7 indicating a very important criterion and 1 an unimportant criterion:

CRITERION	SCORE (1 TO 7)
TOTAL STRUCTURAL COST	5
TOTAL INITIAL EMBODIED ENERGY	2
FRAME CONSTRUCTION TIME	5
TOTAL CONSTRUCTION TIME	7

For example, if all criteria are considered moderately important, a score of say 3 to 4 is assigned to all four. If cost is considered very important and the others only moderate, cost scores 7 and the other three score 3 to 4.

Many thanks

Margaret Rogers

Appendix B

Concordance, weighted and overall performance matrices

Decision Maker DM8 for Manchester

Table B1: Criterion C1 – Cost Concordance matrix (Manchester)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)
(S1)	1	1	1	0	1	1	1	1	1	1
(S2)	0	1	0	0	1	1	1	1	1	1
(S3)	0	1	1	0	1	1	1	1	1	1
(S4)	1	1	1	1	1	1	1	1	1	1
(S5)	0	0	0	0	1	1	1	1	1	1
(S6)	0	0	0	0	0	1	1	1	1	1
(S7)	0	0	0	0	0	0	1	0	0	0
(S8)	0	0	0	0	0	0	1	1	1	1
(S9)	0	0	0	0	0	0	1	0	1	0
(S10)	0	0	0	0	0	0	1	0	1	1

Table B1: Criterion C1 – Cost Weighted matrix (Manchester) DM8

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	0.35	0.35	0.35	0	0.35	0.35	0.35	0.35	0.35	0.35	**3.15**
(S2)	0	0.35	0	0	0.35	0.35	0.35	0.35	0.35	0.35	**2.45**
(S3)	0	0.35	0.35	0	0.35	0.35	0.35	0.35	0.35	0.35	**2.80**
(S4)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	**3.50**
(S5)	0	0	0	0	0.35	0.35	0.35	0.35	0.35	0.35	**2.10**
(S6)	0	0	0	0	0	0.35	0.35	0.35	0.35	0.35	**1.75**
(S7)	0	0	0	0	0	0	0.35	0	0	0	**0.35**
(S8)	0	0	0	0	0	0	0.35	0.35	0.35	0.35	**1.40**
(S9)	0	0	0	0	0	0	0.35	0	0.35	0	**0.70**
(S10)	0	0	0	0	0	0	0.35	0	0.35	0.35	**1.05**
Total	**0.70**	**1.40**	**1.05**	**0.35**	**1.75**	**2.10**	**3.50**	**2.45**	**3.15**	**2.80**	

Table B.3: Criterion C2 - Initial embodied energy Concordance matrix (Manchester)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)
(S1)	1	1	1	1	1	1	0	1	0	1
(S2)	0	1	0	0	1	1	0	1	0	1
(S3)	0	1	1	1	1	1	0	1	0	1
(S4)	0	1	0	1	1	1	0	1	0	1
(S5)	0	0	0	0	1	1	0	0	0	0
(S6)	0	0	0	0	0	1	0	0	0	0
(S7)	1	1	1	1	1	1	1	1	0	1
(S8)	0	0	0	0	1	1	0	1	0	1
(S9)	1	1	1	1	1	1	1	1	1	1
(S10)	0	0	0	0	1	1	0	1	0	1

Table B.4: Criterion C2 - Initial embodied energy Weighted matrix (Manchester) DM8

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	0.12	0.12	0.12	0.12	0.12	0.12	0	0.12	0	0.12	**0.96**
(S2)	0	0.12	0	0	0.12	0.12	0	0.12	0	0.12	**0.60**
(S3)	0	0.12	0.12	0.12	0.12	0.12	0	0.12	0	0.12	**0.84**
(S4)	0	0.12	0	0.12	0.12	0.12	0	0.12	0	0.12	**0.72**
(S5)	0	0	0	0	0.12	0.12	0	0	0	0	**0.24**
(S6)	0	0	0	0	0	0.12	0	0	0	0	**0.12**
(S7)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0	0.12	**1.08**
(S8)	0	0	0	0	0.12	0.12	0	0.12	0	0.12	**0.48**
(S9)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	**1.20**
(S10)	0	0	0	0	0.12	0.12	0	0.12	0	0.12	**0.48**
Total	**0.36**	**0.72**	**0.48**	**0.60**	**1.08**	**1.20**	**0.24**	**0.96**	**0.12**	**0.96**	

Table B5: Criterion C3 – Frame construction time Concordance matrix (Manchester)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)
(S1)	1	0	1	1	0	0	1	1	1	1
(S2)	1	1	1	1	1	1	1	1	1	1
(S3)	1	0	1	1	0	0	1	1	1	1
(S4)	1	0	1	1	0	0	1	1	1	1
(S5)	1	1	1	1	1	1	1	1	1	1
(S6)	1	1	1	1	1	1	1	1	1	1
(S7)	0	0	0	0	0	0	1	1	1	1
(S8)	0	0	0	0	0	0	1	1	1	1
(S9)	0	0	0	0	0	0	0	0	1	0
(S10)	0	0	0	0	0	0	1	1	1	1

Table B6: Criterion C3 – Frame construction time Weighted matrix (Manchester) DM8

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	0.29	0	0.29	0.29	0	0	0.29	0.29	0.29	0.29	**2.03**
(S2)	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	**2.90**
(S3)	0.29	0	0.29	0.29	0	0	0.29	0.29	0.29	0.29	**2.03**
(S4)	0.29	0	0.29	0.29	0	0	0.29	0.29	0.29	0.29	**2.03**
(S5)	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	**2.90**
(S6)	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	**2.90**
(S7)	0	0	0	0	0	0	0.29	0.29	0.29	0.29	**1.16**
(S8)	0	0	0	0	0	0	0.29	0.29	0.29	0.29	**1.16**
(S9)	0	0	0	0	0	0	0	0	0.29	0	**0.29**
(S10)	0	0	0	0	0	0	0.29	0.29	0.29	0.29	**1.16**
Total	**1.74**	**0.87**	**1.74**	**1.74**	**0.87**	**0.87**	**2.61**	**2.61**	**2.90**	**2.61**	

Table B7: Criterion C4 – Overall construction time Concordance matrix (Manchester)

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)
(S1)	1	0	1	1	0	0	1	1	1	1
(S2)	1	1	1	1	1	1	1	1	1	1
(S3)	1	0	1	1	0	0	1	1	1	1
(S4)	1	0	1	1	0	0	1	1	1	1
(S5)	1	0	1	1	1	1	1	1	1	1
(S6)	1	0	1	1	1	1	1	1	1	1
(S7)	0	0	0	0	0	0	1	1	1	1
(S8)	0	0	0	0	0	0	1	1	1	1
(S9)	0	0	0	0	0	0	0	0	1	0
(S10)	0	0	0	0	0	0	1	1	1	1

Table B8: Criterion C4 – Overall construction time Weighted matrix (Manchester) DM8

	(S1)	(S2)	(S3)	(S4)	(S5)	(S6)	(S7)	(S8)	(S9)	(S10)	Total
(S1)	0.24	0	0.24	0.24	0	0	0.24	0.24	0.24	0.24	**1.68**
(S2)	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	**2.40**
(S3)	0.24	0	0.24	0.24	0	0	0.24	0.24	0.24	0.24	**1.68**
(S4)	0.24	0	0.24	0.24	0	0	0.24	0.24	0.24	0.24	**1.68**
(S5)	0.24	0	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	**2.16**
(S6)	0.24	0	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	**2.16**
(S7)	0	0	0	0	0	0	0.24	0.24	0.24	0.24	**0.96**
(S8)	0	0	0	0	0	0	0.24	0.24	0.24	0.24	**0.96**
(S9)	0	0	0	0	0	0	0	0	0.24	0	**0.24**
(S10)	0	0	0	0	0	0	0.24	0.24	0.24	0.24	**0.96**
Total	**1.44**	**0.24**	**1.44**	**1.44**	**0.72**	**0.72**	**2.16**	**2.16**	**2.40**	**2.16**	

Table B9: Overall performance matrix for all criteria (Manchester) DM8

	(S1)	**(S2)**	**(S3)**	**(S4)**	**(S5)**	**(S6)**	**(S7)**	**(S8)**	**(S9)**	**(S10)**	**Total**
(S1)	1.0	0.47	1.0	0.65	0.47	0.47	0.88	1.0	0.88	1.0	***7.82***
(S2)	0.53	1.0	0.53	0.53	1.0	1.0	0.88	1.0	0.88	1.0	***8.35***
(S3)	0.53	0.47	1.0	0.65	0.47	0.47	0.88	1.0	0.88	1.0	***7.35***
(S4)	0.88	0.47	0.88	1.0	0.47	0.47	0.88	1.0	0.88	1.0	***7.93***
(S5)	0.53	0.29	0.53	0.53	1.0	1.0	0.88	0.88	0.88	0.88	***7.40***
(S6)	0.53	0.29	0.53	0.53	0.53	1.0	0.88	0.88	0.88	0.88	***6.93***
(S7)	0.12	0.12	0.12	0.12	0.12	0.12	1.0	0.65	0.53	0.65	***3.55***
(S8)	0	0	0	0	0.12	0.12	0.88	1.0	0.88	1.0	***4.00***
(S9)	0.12	0.12	0.1	0.12	0.12	0.12	0.47	0.12	1.0	0.12	***2.43***
(S10)	0	0	0	0	0.12	0.12	0.88	0.65	0.88	1.0	***3.65***
Total	***4.24***	***3.23***	***4.71***	***4.13***	***4.42***	***4.89***	***8.51***	***8.18***	***8.57***	***8.53***	

S1 (7.82 – 4.24) = 3.58

S2 (8.35 – 3.23) = 5.12

S3 (7.35 – 4.71) = 2.64

S4 (7.93 – 4.13) = 3.80

S5 (7.40 – 4.42) = 2.98

S6 (6.93 – 4.89) = 2.04

S7 (3.55 – 8.51) = -4.96

S8 (4.00 – 8.18) = -4.18

S9 (2.43 – 8.57) = -6.14

S10 (3.65 – 8.53) = -4.88

The ranking of the options, by decision maker DM8, using the Promothee 1 method is set out below:

1st **Option S2** (Slimflor® beams and deep deck floor un-propped)

2nd **Option S4** (Composite beams and composite floor slab)

3rd **Option S1** (Slimflor® beams and pre-cast hollow core slab)

4th **Option S5** (Cellular beams or castellated beams and composite slab)

5th **Option S3** (Slimflor® beams and deep deck floor propped)

6th **Option S6** (Composite beams with web openings)

7th **Option S8** (Pre-cast hollow core units on R.C. edge beams)

8th **Option S10** (Precast double T units on reinforced concrete edge beams)

9th **Option S7** (Reinforced concrete flat slab)

10th **Option S9** (Reinforced concrete waffle slab)