Integrated Life Cycle Design applied to Concrete Residential Buildings

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Summary

Design and procurement based on whole life appraisal can improve functional quality and, therefore, the overall cost effectiveness of buildings. Empirical studies support this claim, yet a small proportion of house building projects adopt life cycle design principles. In this regard, whole life appraisal is examined by considering design procedures and the functional characteristics of the building. The initial part of the work adopted life cycle costing, life cycle assessment, service life planning and integrated design principles to concrete residential buildings. A qualitative method to evaluate the indoor climate was also applied. A toolbox for integrated life cycle design was compiled and parameter studies were undertaken to indicate potential improvements in regard to life cycle quality. In the second part of the work the toolbox is employed on real projects to evaluate its practicability and to assess the potential impact on building performance. The first application was a study on alternative façades and ventilations systems for a project comprising four 26 flat residential blocks in Malmoe, Sweden.

Energy in buildings, Life cycle design, Life cycle costing, Life Cycle Assessment

1. Introduction

It is expected that by applying a <u>life cycle perspective</u> the long-term quality including cost effectiveness and environmental performance of buildings can be enhanced. It is furthermore assumed, that the overall performance of a building is dependent on interaction between components, systems and materials and thus that a <u>holistic design</u> approach is beneficial [1]. Other industries often base their product development on these principles, however by the design of buildings they are rarely used.

This work aims at developing and testing a simplified integrated life cycle design tool kit including economical and environmental whole life appraisal. The tool kit is general, incorporating all materials, systems and functions relevant for houses. It is however primarily intended for life-time optimisation of concrete multi-dwelling buildings. Life cycle design methods such as Service Life Design, Life Cycle Costing or Whole Life Costing and Life Cycle Assessment have been used for decades. Reliable input data for calculations are in some cases, such as operating costs for buildings, available. Other data, for example quantitative environmental information on components and materials incorporated or used for maintenance of the building, data are not complete or accessible, in which case simplifications are necessary.

In order to rank possible design alternatives there are two possible approaches. One is to define a fixed set of requirements on the building and calculate the life cycle cost for each alternative. The environmental 'cost' can be included with a socio-economic cost estimation. Normally, the alternatives have different functional properties and quality, which should be addressed in the life cycle comparison. In that case a possible approach is multiple attribute decision analysis, 'MADA' [2]. MADA supports ranking between a finite set of alternatives, in relation to any predefined set of different attributes such as acoustics, aesthetics and economy.

2. The simplified integrated life cycle design toolbox

2.1 Integrated Life Cycle Design

The specific features of Integrated Life Cycle Design, ‘ILCD’ are; i) life cycle appraisal and; ii) the pursuit of a holistic perspective on the building and the requirements that have to be addressed. These features have been introduced into the design process according to Figure 1.

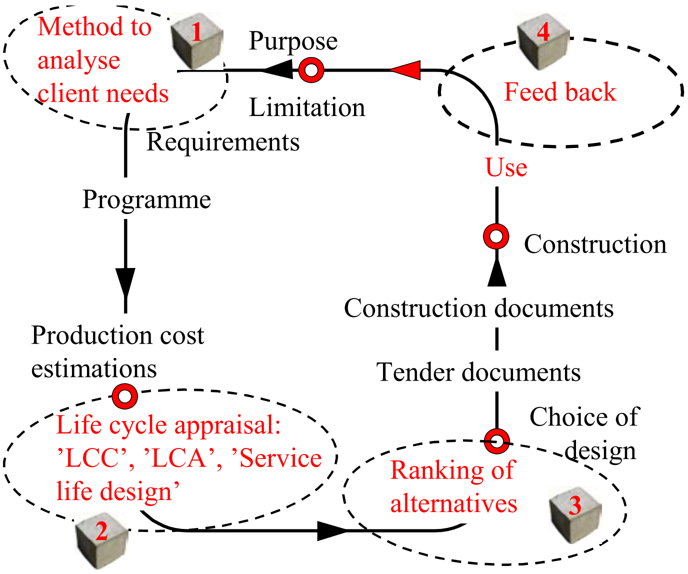

Fig. 1 Integrated Life Cycle Design procedure

1 <u>Analysis of client needs</u>. Short- and longterm needs are systematically defined, analysed and prioritized. Methods from quality technology, such as Quality Function Deployment [3], can be used

2 <u>Life cycle appraisal</u>. Comprising ’Service life planning’, Life Cycle Costing and Life Cycle Assessment is applied to quantify life cycle consequences of alternative designs

3 <u>Ranking methods,</u> such as Multiple Attribute Decision Analyses to aid the choice of design in regard of several different aspects. [2]

4 <u>Feed back</u>. Information from production and use of the building is systematically fed back to the design team and management

2.2 Tools

Further to the traditional design instruments, dealing with building physics, structural analysis and so on, ILCD includes methods to assess the life cycle consequences of design alternatives. It also supports analyses of client needs and ranking of alternatives [1].

2.2.1 Economy

The present value of the life cycle costs is used for economical evaluation. For a modern Swedish residential building the costs for production (investment), heating and periodic maintenance are the largest single factors in regard of life cycle economy [1]. These items are highly dependent on the design of the building while other costs, such as administration or waste handling, are not.

A spreadsheet tool for the calculation of present value of life cycle costs for multi-dwelling buildings including a database on periodic maintenance costs was developed.

2.2.2 Global environment and resource use

A full environmental evaluation of a product can be accomplished by Life Cycle Assessment, ´LCA’. For the ordinary design situation LCA is a too onerous task, as environmental and life cycle data are not yet available for all products and materials incorporated in buildings. Energy use during the operating phase, that is heating, cooling and electricity has been defined as the single most important environmental aspect for buildings in Sweden [4]. Energy use was thus selected as an environmental indicator. The energy use during operation for the specific design alternatives and climatic conditions is estimated with an energy balance programme. A spreadsheet tool calculates the resulting emissions of CO_2, NO_X, SO_2 and VOCs based on the specific energy sources, and the socio-economic cost for these emissions, according to Swedish National Roads Administration [5]. Table 1 shows an estimation of the environmental impact of the life cycle energy use of a new 2900 m^2 residential building in south Sweden. ‘Production’ refers to energy used at the building site and for the production and transport of raw materials and components. ‘Use’ includes household and common electricity, space heating and hot tap water for a life span of 60 years.

Table 1. Environmental impact of life cycle energy use. Example of application of estimation tool

	Energy use	CO_2	NO_X	SO_2	VOC	Socio economic cost (k€)
	MWh	Ton	Kg	kg	kg	
Production						
Fossil fuel	1250	418	1081	1816	104	81
Swedish electricity	1250	54	85	56	17	10
Sum production	2500	472	1166	1872	121	91
Use (60 years)						
Swedish electricity	5580	239	378	249	75	43
District heating	15204	1801	4888	4598	57	343
Sum use	20784	2040	5266	4847	132	386
Total	**23284**	**2511**	**6432**	**6718**	**253**	**477**

2.2.3 Methods to analyse the requirements on the building and to rank alternative designs

To organise the collection, interpretation and definition of the client's needs as regards functionality, a product development method such as Quality Function Deployment, *QFD* [3], can be applied. QFD is used to support product optimisation in the design phase. QFD has been successfully applied in the manufacturing industry since the early 1980s. QFD is a method for (i) developing a design quality aimed at satisfying the customer and (ii) translating the consumers' demand into design targets and major quality assurance points, to be used throughout the production stage. QFD is thus a systematic way of tuning the product features to the client requirements and of documenting the decisions in the design process.

The simplest way to rank possible design alternatives is to define a fixed set of requirements on the building and calculate the life cycle cost for each alternative. The environmental 'cost' can be included by a socio-economic cost estimation as described in 2.2.2. Often, however, the alternatives have different functional properties and the value of these differences should be assessed. Multiple Attribute Decision Analysis, 'MADA' [2]. is a tool to rank a finite set of alternatives, in relation to a predefined set of different attributes that can be measured quantitatively or qualitatively, for instance acoustics, flexibility, aesthetics and economy. The following example presents a MADA ranking of the actual design: 'R' of a multi-family dwelling building in Svedala, South Sweden in comparison with two alternative designs: 'Y and Z'. R; concrete frame with brick clad curtain wall façade, Y; concrete frame with concrete sandwich wall façade, Z; timber frame with a wood panel façade.

Figure 2 displays first step of the analysis - the hierarchical tree structure, including all attributes selected for comparison, and their relative importance. In this case life cycle cost is regarded as the most important attribute and attached 40% weight.

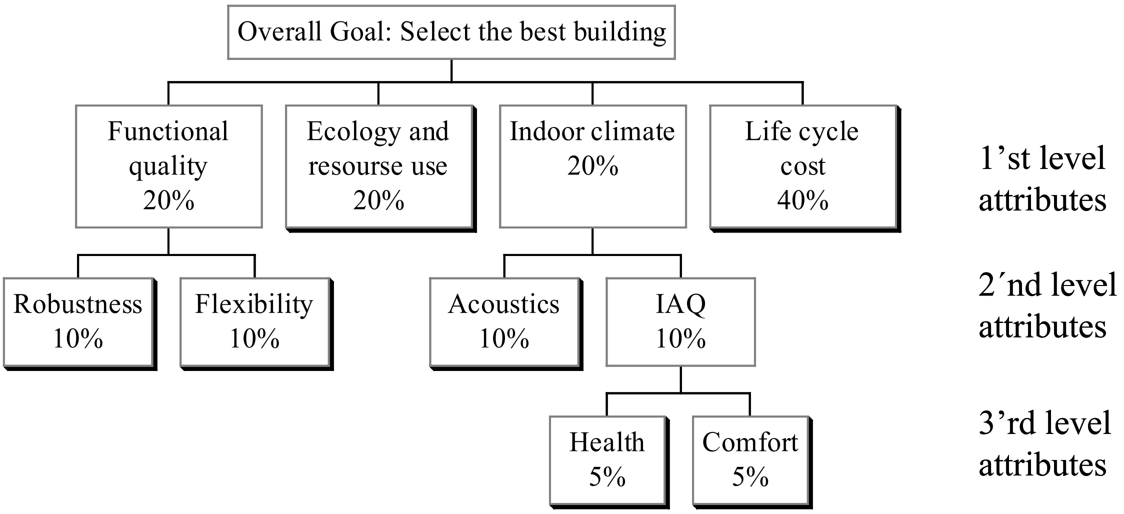

Figure 2. MADA tree structure to rank alternative designs according to selected attributes

Table 2 shows the resulting decision matrix showing the assessment of three different design alternatives. The performance indicated for each attribute in the matrix is digitalised and to facilitate a direct ranking by adding the variables to one single value for each design alternative, see Table 3.

Table 2. MADA decision matrix

Attribute			Performance of alternative			
Level 1	Level 2	Level 3	R	Y	Z	Unit
Functional q.	Robustness		Excellent	Excellent	Accept.	Verbal
	Flexibility		Very good	Excellent	Accept.	Verbal
Ecology*			6700	6600	6800	kWh/m²
Indoor climate	Acoustics		B	B	C	Sound Class
	IAQ	Health	Very good	Very good	Very good	Verbal
		Comfort**	36	12	60	Days/year
LCC. 50 years			1770***	1780***	1770***	€/m²

Quantified as life cycle energy use, **Indoor temperature exceeding 27ºC, * Initial costs were higher for R and Y while operation cost are higher for alternative Z*

Table 3 displays the digitalised ranking. R is the reference alternative and the rating for each attribute indicates the weight put to that attribute in relation to the others. The sum is thus 1,0 for alternative R. In this example the attributes attached relatively low importance, such as robustness, flexibility (10% each) and comfort (5%) are decisive. This is due to nearly equivalent performance in regard of the more heavy weighted attributes.

Table 3. Ranking of design alternatives according to MADA

	R	Y	Z	R is selected as reference thus adding up to the sum = 1,0. The ranking values for each attribute reflect the relative importance attached to that particular attribute. In this case: ☐ Functional quality 20% divided on robustness and flexibility 10% each. ☐ Ecology 20% ☐ Indoor climate 20% divided on acoustics 10% and health and comfort 5% each ☐ Life cycle cost 40%
Robustness	0,1	0,1	0,02	
Flexibility	0,1	0,125	0,067	
Ecology	0,2	0,2	0,2	
Acoustics	0,1	0,1	0,067	
Health	0,05	0,05	0,05	
Comfort	0,05	0,08	0,03	
LCC. 50 years	0,4	0,40	0,40	
Sum	**1**	**1,05**	**0,82**	

It should be pointed out that the digitalisation and addition of the different values to one single sum is a sensitive procedure. It is not expected that MADA should be applied from scratch in any regular house-building project. It is suited for repeat order clients or producers of building systems to optimise the ‘product’ in relation to the demands of the clients and other requirements.

2.2.4 Verification of the life cycle design tools and parameter study

The tool kit developed was verified by a study on the performance of existing modern Swedish concrete multi-dwelling buildings and with national statistical data on costs and energy use. Production and operating costs and energy use were mapped and compared with calculated values. An indoor climate survey was also conducted to investigate its practicability as feed back tool.

Parameter studies were undertaken with the tool kit. Also minor differences in performance, for instance in regard of energy use due to orientation of windows, air tightness of climate shell or thermal mass of the building, become significant in the life cycle perspective. Differences in periodic maintenance or design life of materials and components are also important.

3. Application in a real design situation

3.1 The project

The toolbox was applied in practise for the first time by a residential building project in Malmoe, Sweden, comprising four 26-flat residential building blocks. The task was to evaluate the life cycle consequences of alternative designs in regard of façade and ventilation system for the remaining two houses after the construction of two first buildings had already been started. The original design was load bearing, aerated lightweight concrete block façades and mechanical exhaust ventilation. The alternatives were curtain wall brick façade and balanced ventilation with heat recovery. Precast concrete sandwich walls were also included, however only in regard of operating characteristics, so the full life cycle comparison could not be made for that case.

3.2 Survey on design process

The work was started with a qualitative survey among the design team on if and how the issues presented as the cornerstones of ILCD, in Figure 1 above, were addressed in this particular project.

No 1: Analyses of clients (residents and owner) needs: This was based on long experience of the performance of materials and systems available and profound understanding of the local housing market. Furthermore the city planners also influence the decisions. No systematic routine to transform the requirements with the technical characteristics of the building was employed.

No 2: Life cycle appraisal. Materials and systems were selected on the basis of experience of the developer, design team and contractor. No quantifications were made, neither in regard to economy, or global environment. To guide facilities management, a maintenance manual is compiled including maintenance actions and intervals, for the specific materials and systems in the building. This is done after the completion and is thus not a design activity.

No 3: Ranking of alternatives where made in regard to production cost and, for the selection of façade surface material, strongly influenced by the city planning authority.

No 4: No specific routines for feedback to the design team were employed, from the production process or the user phase. There was a consensus among the design team that this is a general improvement area for the sector. The developer plans a qualitative survey on indoor climate directed to residents to be conducted the second year after occupancy.

3.3 Calculations and results

The calculations include life cycle costs, energy balance during operation and socio-economic cost, referring to the emissions to air generated by energy use, over a lifecycle of 50 years. In Table 4 the results of the calculations are presented as the difference to the alternative defined as reference.

Table 4. Life cycle cost and socio economic cost (€/m^2, dwelling space) over 50 years. Difference to reference design alternative (Aerated lightweight concrete block façade 'ALWB' and mechanical exhaust ventilation)

Ventilation	Mechanical exhaust vent.			Balanced ventilation		
Façade	ALWB	Brick	Concrete	ALWB	Brick	Concrete
Production cost façade	-19		0	-19		-19
Production cost ventilation	0	0	21	21	21	0
Periodic maintenance façade	-3	-2	0	-3	-2	-3
Periodic maintenance ventilation	0	0	13	13	13	0
Heating	-9	-10	-89	-89	-100	-9
Electricity for fans	0	0	7	7	7	0
Loss of usable area	0	0	31	31	31	0
Life cycle cost. Difference	**-31**		**-18**	**-40**		**-31**
Socio-economic cost. Difference	**-62**	**-13**	**-35**	**-80**	**-31**	**-62**

The cost categories that differ between the alternatives are production, periodic maintenance, heating, and operation of fans for the ventilation system and finally loss of usable area due to more space needed for the ducts and apparatus with balanced ventilation.

The calculations indicate that the proposed alternatives to the original design, both in regard to ventilation system and façade were favourable. Sensitivity analyses on energy price increases confirmed the advantages of change. However, the extra effort in regard to design and change of production procedures was deemed to costly to motivate a change at this rather late stage. This example showed that if life cycle design principles had been applied from the beginning of the design, other technical solutions might have been selected.

4. Discussion, Conclusions and Acknowledgements

The tools and data for life cycle design can be obtained but are, however, not easily available for the designers. Life cycle estimations in regard to economy and environmental performance can be made with reasonable accurateness.

The methods to transfer the functional requirements on the building to technical specifications, QFD, and to rank alternative designs, MADA, are relevant for a producer, or a repeat order client, by the development of building concepts, rather than for a single specific project. It is also possible to extract from these methods only the clear and systematic way to table requirements on the building and performance of alternatives.

A simplified procedure including life cycle cost and socio-economic costs can be applied in the ordinary design situation, such as in the example in section 3. Note however, that the functional quality of the different alternatives proposed in the example was not thoroughly evaluated. For instance the acoustic behaviour is different between the alternatives and with balanced ventilation the thermal comfort during winter is likely to improve according to experiences from indoor climate questionnaires. The systems also represent different technical complexity and risk of failure. These differences should be assessed and taken into account in order to establish the optimal design.

The concept can be used for a limited decision situation, such as presented in section 3. However, to cover the interaction between systems and structures a general analysis of the whole building is preferred. For example, the demand on air tightness of the climate shell is larger with balanced ventilation due to higher risk of moisture problems inside the wall, caused by overpressure inside the building. The selection of one system thus influences the choice of another system or structure.

The work will continue with further demonstrations on real projects were the full tool kit, including the use of MADA and QFD will be employed.

The potential in regard of improved life cycle performance is substantial. In the pursuit of sustainable construction a holistic life cycle perspective, by design and procurement, is a necessity.

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