Integration – the key and the way towards life-time engineering

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ABSTRACT: The real estate and construction sector is in change that is mainly driven by increasing requirements concerning the performance of constructions during their whole life-time: the overall performance of buildings and constructions need to be managed from cradle to grave, and with a great emphasis on customer and user needs.

The true success of the change in relation to demands depends largely upon management of innovations and processes. Methods, tools and skills to handle data and knowledge from various domains have become crucial. In order to have a reliable basis for new practices, research and higher education need to work on science-based approaches. This concerns all aspects from prediction of safe life-time of constructions to methods of integration.

This paper gives an overview of relatively new disciplines – like simulation-based engineering science – and technologies – like Building Information Modelling – that can be applied to support life-time engineering through integration and synergy.

1 INTRODUCTION

Sustainability is fundamentally a concept that brings along needs for learning, working and research across boundaries. In order to guarantee true progress in the construction and real estate sector, knowledge from various scientific traditions are to be combined and new integrative methodologies to be established. New conditions will affect ways of communication as well as the fields of professions.

The concept of sustainable construction aims at integrating the objectives of sustainable development into the construction activities. It is generally understood in relation with the environmental performance of products and assets (environmental sustainability). According to the report by the EU's Taskforce for Sustainable construction (Lead Market 2008), the concept should refer to a balanced economical, ecological and social approach. This formulation comprises three bottom-line dimensions of sustainability - or "three pillars that are people, planet and profit". In addition, each pillar should be considered from the life-time points of views.

In the Agenda 2001 of the EU Working Group on Sustainable Building (Agenda 2001), Performance Based Building was listed as an emerging area to be funded. The European PeBBu network together with CIB, International Council of Research and Innovation in Building and Construction has studied and promoted this approach. Several points of views are recognized that relate performance-based approach to sustainable construction, e.g. Trinius et al (2005) emphasize the importance of service life design and Lützkendorf et al (2005) state that performance approach can be used in every phase of a building's life-cycle.

Spekkink (2005) describes the performance-based design as follows: "Designers have to deal with systematic interrelations between different performance specifications, which often relate to different fields of expertise. Thus, the performance-based approach calls for integral design, with parallel, inter-related contributions from all design disciplines involved." Needs to understand human behaviour – and to model it – are obvious for example in relation to accessibility, consumption of energy and water, indoor climate, noise, vibrations, emergency and evacuation planning. Comfort, convenience and experience are an essential part of customer-oriented design and building.

When sustainability is considered, needs to integrated approaches are recognized not only in the building and construction projects, but also in education, applied sciences and product development. According Kohler & Hassler (2002), the management of building stocks cannot be improved without taking into account the interrelations between economic, physical, social and cultural aspects, and thus research efforts should be directed to the integration of different views.

A scientific debate is ongoing about the level of the integrated methods, which highlights the difficulty of the area. In the EC Workshop (2007) on Sustainability research, Bijker from Univ. of Maastricht argued that inter-disciplinarity is risky business for scientists (due to evaluation structures and publication possibilities) and stands the best chance when it is acknowledged that science requires strong disciplines as a basis for interdisciplinary engagements. However, possible scientific problems are regarded as less important in practice where there are true needs to understand and manage complex relations (figure 1).

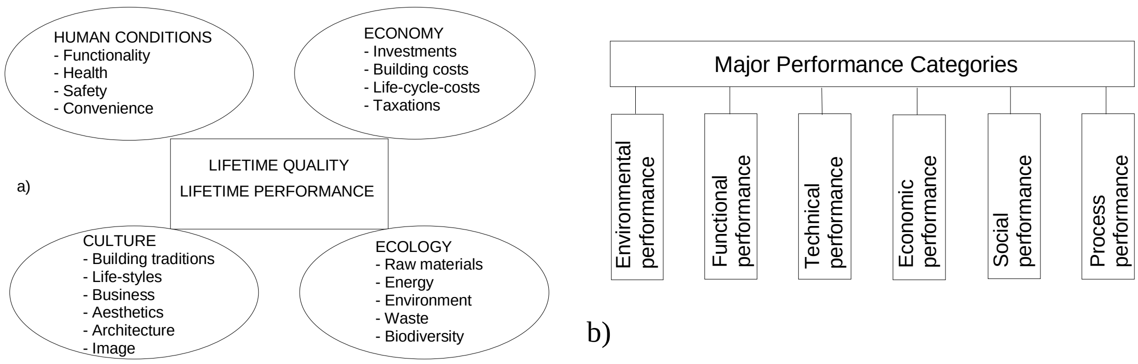

Figure 1. a) Knowledge from various sources in life-time engineering of bridges (modified from Söderqvist et al 2005), and b) Aspects of performance-based design (Lützkendorf et al 2005)

The aim of this paper is to serve as a work document of the COST Action C25 in development of integrated methods of life-time engineering, and introduce problems and methods related to the multifaceted issue of “integration”. Methods of integration comprise collaborative learning and working methods as well as new approaches to link, combine and handle information and data from various disciplines. It is obvious that modern computing technologies and software play an essential role in the evolution and usability of integral methods. The subject will be dealt in the three areas: science-based R&D, simulation-based engineering and performance-based building.

2 SCIENCE OF INTEGRATED APPROACHES

Engineering sciences are very much about integration: they are dealing with actions and reactions or impacts and responses, and on both sides of these pairs, different scientific methods are applied. As an elementary example of integrated methods can be given those of structural safety that combine empirical and statistical information from meteorological data, material properties and structural experiments, and use mechanics and reliability analysis in modelling the performance and further development of design methods (Figure 2). Similarly, knowledge on material properties and on climatic variables is needed to predict the thermal and moisture behaviour of structures. The climatic models are also important in modelling energy consumption or degradation of materials.

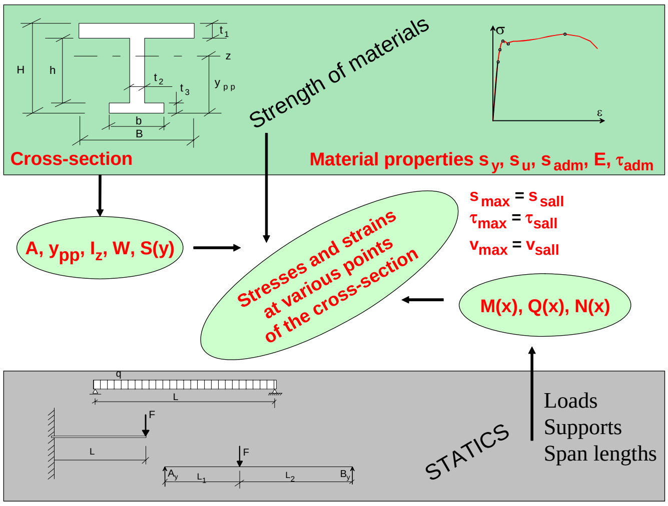

Figure 2. Elementary example of an integrated method.

At a very general level, scientific methods are categorized as quantitative and qualitative ones, and they are in common characterized with pairs of words like objective - subjective, deductive - inductive, galilean – aristotelic, explanation – understanding. However, the differences can be regarded as fuzzy (Lele et al 2005).

The use of various methods in one study is called "triangulation". The term comes from the land-measurements that applied rules of angles and side lengths of a triangle. Reasoning for the triangular approach is that the problem can be explained better with results from various perspectives. Denzin (1978) has divided triangulation to four classes:

- Material of a study can be collected from various sources and represent various physical forms or expressions.
- When several scientists work on the same problem, they have to communicate well about all scientific issues.
- Various theories can be applied at the same time to one object.
- Various methods to collect material and analyse it can be applied to study one problem from various points of views.

Triangulation is an essential part of the development of disciplines. It can be said that usually one discipline applies many methods. On the other hand, a scientific debate concerns benefits and appropriateness of triangulation as there are risks of conceptual misunderstanding and acceptance of conflicts. The application of triangulation principles to the integration of scientific methods can result in a scheme like the one that is illustrated in Figure 3.

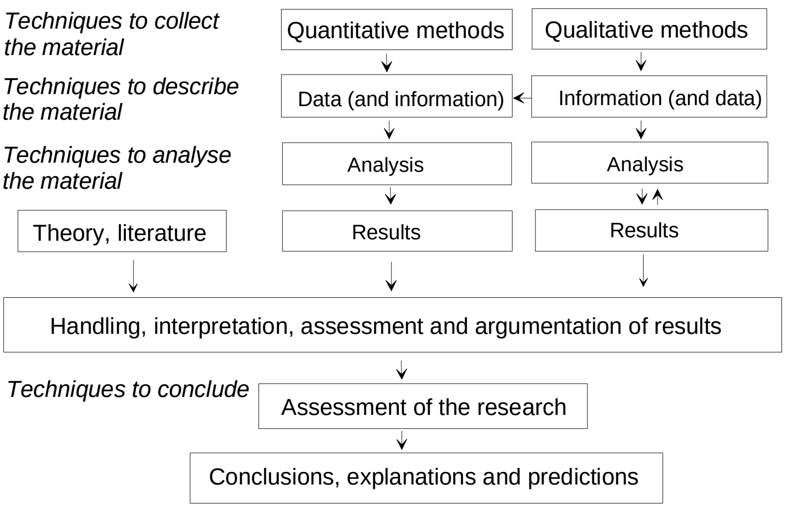

Figure 3. Triangulation of various quantitative and qualitative methods.

In general, a scientific research method comprises the following techniques (Niiniluoto 1980):

1) Techniques to collect the research material, like theory to plan experiments, sampling theory, use of literature, source critics, external observation, participative inquiry, action research, ethnography, systematic test, measurement, interviews etc.;

2) Techniques to describe the research material, like classification of qualitative material, codification, thematic cards, arrangement of data, statistical identification, methods of system theory, graphics, pictures;

3) Techniques to analyse the research material, like quantification, like statistical methods, factor analysis, multi-variate methods, themes, discursion analysis, conversational analysis;

4) Techniques to conclude: like theory of statistical tests, decision-making theory, causal analysis.

Various approaches can be applied to plan and conduct an integrated project. Definitions of scientific approaches are presented in the following scheme (Figure 4).

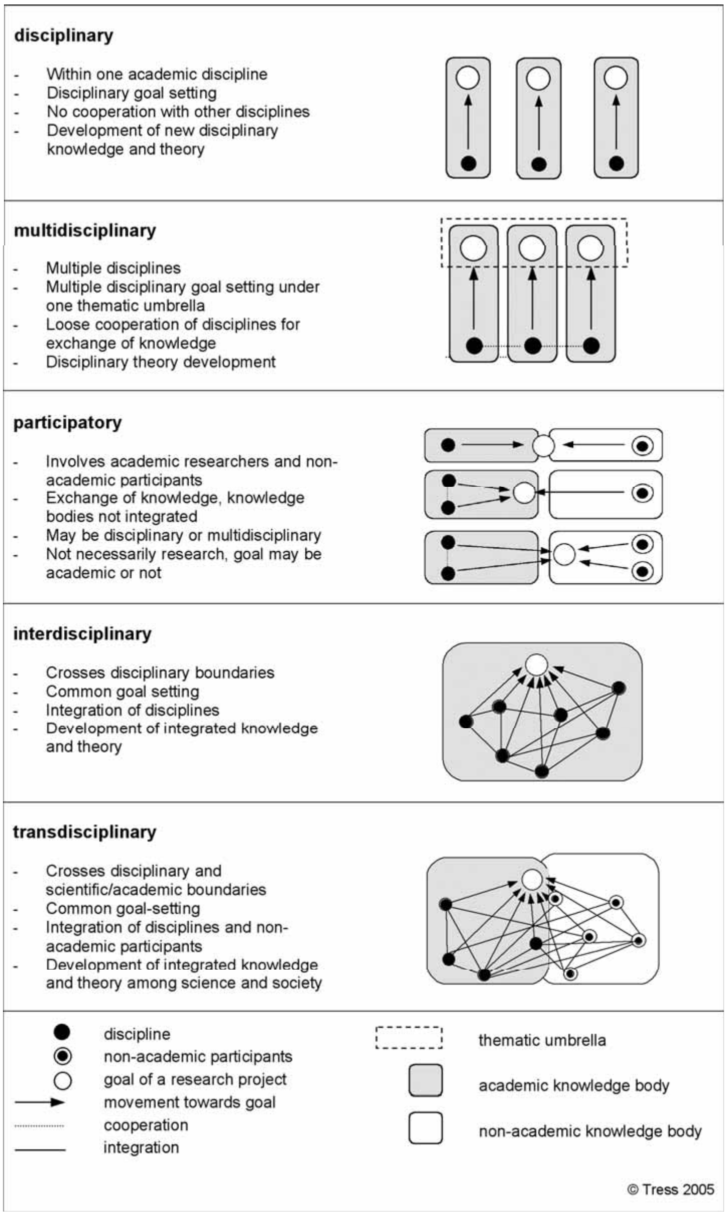

Figure 4. Definitions of multi-disciplinary approaches (Tress 2005).

Bammer (2005) argues that there is a need and time for a new Integration and Implementation Science, whose theoretical and methodological foundations will be:

- Systems thinking and complexity science, which orient us to looking at the whole and its relationship to the parts of an issue.
- Participatory methods, which recognize that all the stakeholders have a contribution to make in understanding and, often, decision making about an issue.
- Knowledge management, exchange, and implementation, which a) involve appreciating that there are many forms of knowledge and ways of knowing (diverse epistemologies), b) provide enhanced methods for accessing knowledge, realizing that both volume and diversity are current barriers, and c) involve developing better understanding of how action occurs - in other words, how policy is made, how business operates, how activism succeeds, and how action is and can be influenced by evidence.

Similar thoughts are presented about the necessity to establish a “Sustainability Science”; a quarterly journal with this title was established in Japan in 2006 that is related to collaborative efforts of several Japanese universities. The needs to understand relations inside complex systems and between them have on the other hand led to demand for integrated analysis, and on the other had increase of computing capacity has offered possibilities to develop studies on complex systems in nature, society and science. More often, system theory and system approaches are highlighted as a framework to analyze and/or describe complex relations and results from these relations.

A holistic and integrated approach means that a large number of variables affecting each others and the overall system will be considered, with probabilistic and reliability studies. In a real integrated project, advanced mathematics is usually the backbone of methodology. An example of various mathematics and techniques in development of life-cycle management programme “Lifecon LMS” is presented in figure 5.

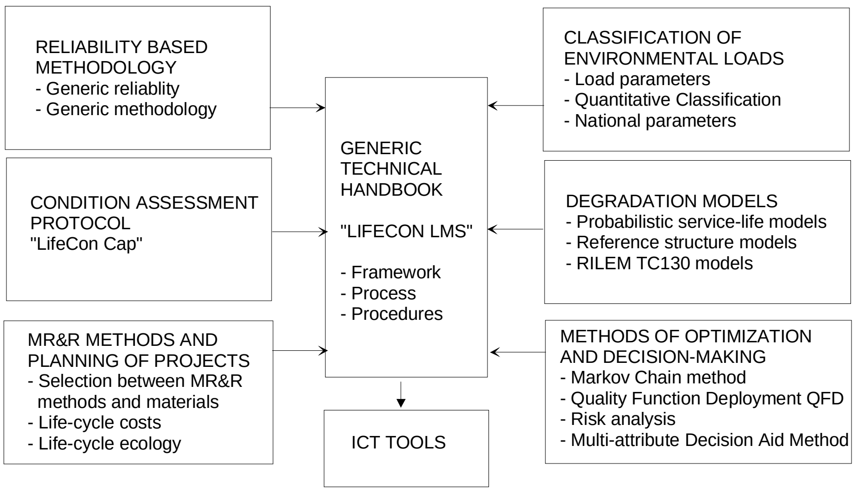

Figure 5. Roles of mathematics in a life-cycle management programme LMS (Söderqvist et al 2004).

In research related to sustainable development, methods of “futuring” are of great importance, and add one dimension to the complex context. The methods to watch trends give us the way to “convert knowledge of what has happened in the past into knowledge about what might happen in the future” (Cornish 2004). Examples of applications can be found e.g. in European projects concerning energy issues like modelling of energy use in the building stock in ECONER (Kohler et al 2002), road-mapping R&D on performance-based building in PeBBu (Foliente et al 2005) and scenarios in the NEEDS (EC DG Research 2007)

3 PERFORMANCE-BASED DESIGN AND BUILDING

Methodologies to manage construction projects from design to use are nowadays of greater importance than ever due to increasing complexity of buildings and building processes, rapid changes of user needs and market environment, goals of sustainable development and demands for faster delivery schedules. For the management of the buildings performance, the value tree analysis offers a logical way to organize the various performance objectives, to evaluate their value and relations, to generate technical criteria and potential solutions and to incorporate rating and verification methods in the framework (Figure 6).

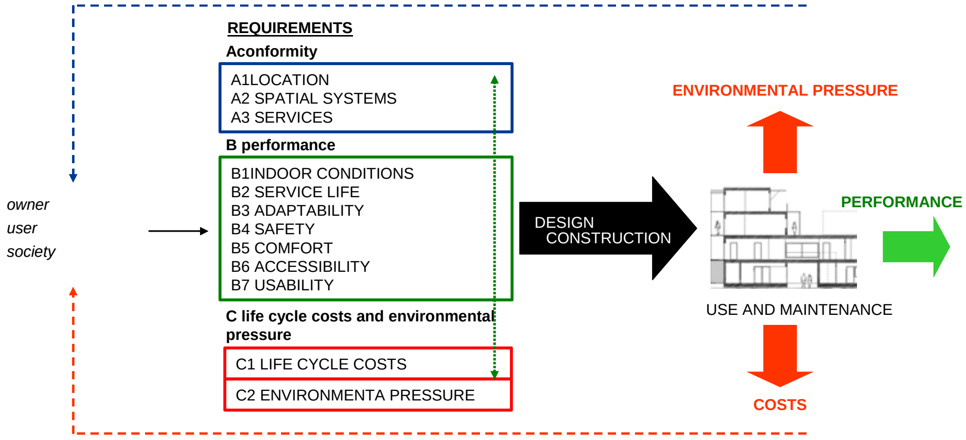

Figure 6. From objectives towards evaluation – the VTT approach to Performance Based Building.

The building performance analysis from the point of view of fitness for use, or fitness for purpose, consists of the following steps

- Gathering qualitative objectives of a building and its immediate surroundings
- Defining the performance objectives to levels so that corresponding technical solutions can be designed
- Selection of evaluation methods, including environmental assessment and cost estimations.

Based on the hierarchy of performance objectives and their targeted qualities, alternate design and technical solutions can be developed. The capability of different solutions to fulfil the performance criteria can be studied with verification methods. Verification methods are nowadays most often various simulation programs which handle large input data and use theoretically sound formulae.

According to the report of National Science Foundation (the U.S.A), simulation-based engineering science is defined as the discipline that provides the scientific and mathematical basis for the simulation of engineered systems. According to the NSF Report (2006), it "fuses the knowledge and techniques of the traditional engineering fields with the knowledge and techniques of fields like computer science, mathematics and the physical and social sciences. As a result, engineers are better able to predict and optimize systems affecting almost all aspects of our lives and work, including our environment, our security and safety, and the products we use and export."

Simulation-based engineering sciences are the basis to sustainable construction technologies and operation of facilities. Modelling and simulations are already extensively used in some areas like structural and fire safety of structures. In the future, various models and simulations will be integrated and the scale of multiple sub-systems will be greater.

The previously mentioned NSF Report (2006), models of "Digital City" are possible although it would require the acquisition of static and dynamic data of unprecedented detail. A logical extension of the Digital-City concept is that of the Digital Ecosystem, which may be artificial (such as a city) or natural (such as a forest, watershed, continent, or even the entire planet). However, a great amount of research must pioneer the way to these visions. The following are listed in the Report as a few of the areas requiring development:

- Quantitative models of the processes to be simulated must be developed. For many of those processes, models of some level of fidelity already exist, or they are being developed for narrower engineering purposes. For example, we lack sociological models that can help us describe or predict the response of populations to crises. In addition, we need better models for the evolution of natural ecosystems such as forests or lakes.
- A comprehensive simulation system is required that integrates detailed models of a wide range of scales. Some of the issues are generic, but others are problem specific.

- New models of exceptional fidelity are required. The development and validation of such models entail the acquisition of data of extraordinary detail. As a result, the development of the Digital City and Digital Ecosystem will inevitably put pressure on the experimental sciences and theoretical research to meet the demand for copious data. Furthermore, the real-time simulation of some applications will drive developments in sensors and the communication infrastructure, both of which must support streams of data. In addition, we need to develop the simulation techniques that can accommodate the data streams.
- A better understanding of the role of uncertainty is required. Some degree of uncertainty is inevitable in the ability of a model to reflect reality and in the data the model uses. We need to find ways to interpret uncertainty and to characterize its effects on assessments of the probable outcomes.

Modelling and simulation of building have been developed in many fields. Also, many combinations have been established for integrative modelling which is explained by Clarke (2001) from energy simulation points of view: “The aim of integrative modelling is to preserve the integrity of the entire building/plant system by simultaneously processing all energy transport paths at a level of detail commensurate with the objectives of the problem in hand and the uncertainties inherent in the describing data. To this end, a building should be regarded as being systemic (many parts make the whole), dynamic (the parts evolve at different rates), non-linear (the parameters depend on the thermo-dynamic state) and, above all, complex (there are myriads intra- and inter-part) interactions. To achieve high modelling integrity, a simulation program aims to preserve these intrinsic characteristics.”

The modelling and simulation are used also to analyse the condition of a building stock in an area, suburb, city or a country. In a model, typical buildings are rated for specific annual energy consumption per m^2, and then the surface of each age-class is multiplied by the specific annual energy consumption to predict the overall consumption (Kohler & Hasler 2002). Validation of these models can be achieved by comparing the sum of estimated consumption to the statistics.

Virtual reality (VR) and simulation technologies used for visualisation support digital communication during the construction process, and of the expected results to customers and occupants. Visualisation of construction projects allows customers and users to get a look and feel for the construction before it is actually built. During the construction process, designs can be improved, and clashes and inconsistencies can be examined and eliminated. Furthermore, these technologies improve cooperation as non-technical staff and end-users can understand the project in a better way than simply looking at drawings and designs.

Clarke (2001) gives an excellent example of the communication capacity of integrated modelling and visualization using ICT: based on simulation technologies, the distribution of properties of air in 3-D of a room can be calculated. On the other hand, the limit values have been got from other fields like medical or behavioural studies. Comparing these two sources of data, simple drawings can be produced to show the areas of satisfactory or unsatisfactory performance of facilities.

Decision-making becomes more complex when the context moves from product/material level to whole building to whole site development or portfolio of buildings scale, and when the key variables increase. The availability of technology-based decision-making tools alone is no longer sufficient to predict outcomes at higher levels of complexity; the influence of human decisions, behaviour and actions, and the dynamic relationships between and among ‘actors’ and physical systems need to be explicitly taken into account. This means that performance models based on complex systems need to be employed for both scenario planning and evaluation. This would allow practical applications of the performance concept beyond buildings and into the wider context of development (Becker et al 2005).

The same situation happens in the service life design where the scale of verification of durability extends from simplistic design conditions to statistical models. The simplest approach to try to achieve targeted years of service life is to follow simple design rules. The opposite approach is performance based design that would use mathematical and theoretical models for durability, for which methods are under development.

In design, the definitions related to durability are often selected based on the ISO standard 15686, and the most important of them are the estimated service life and reference service life of component: estimated service life depends upon the reference service life together with seven multiplying factors. The stochastic nature of the service life may be taken into account in the reference value. The quality of manufacture, design and construction, environmental conditions as well as use and maintenance are taken into account with the multiplying factors but they may also be included in a service life model.

In decision making, the estimated service life is evaluated against the target or limit that has been defined either from structural, economic or aesthetic points of views. The reliability of service life design is greatly dependent on the methods to define the reference service life or the durability models and values chosen for the multiplying factors.

It is expected that the integration and synergy of the new disciplines needed to support lifetime engineering and performance-based design and building can only be managed through the use of new design tools and methodologies like Building Information Modelling (BIM).

Building Information Modelling provides the potential for a virtual information model to be handed from design team to contractors and the owner, each adding their own additional discipline-specific knowledge and tracking of changes to the single model. BIM (Kiviniemi et al 2007) is an object-oriented AEC-specific model, a digital representation of a building, to facilitate exchange and interoperability of information in digital format. The model can be without geometry or with 2D or 3D representations. The result is anticipated to greatly reduce the information loss that occurs when a new team takes "ownership" of the project as well as in delivering extensive information to owners of complex structures far beyond that which they are currently accustomed to having. BIM covers geometry, spatial relationships, geographic information, quantities and properties of building components (e.g. manufacturers' details). BIM can be used to demonstrate the entire building life cycle including the processes of construction and facility operation. Quantities and shared properties of materials can easily be extracted. Scopes of work can be isolated and defined. Systems, assemblies, and sequences are able to be shown in a relative scale with the entire facility or group of facilities.

BIM design method goes far beyond switching to a new software. It requires changes to the definition of traditional architectural phases and more data sharing than most architects and engineers are used to. The potentialities are enormous but its development is still very young and the effective use of integrated BIM for information share requires open standards.

Current development work of the life-cycle assessment methods concentrates to establishing links between LCA software tools and design tools. The analysis software utilises object orientated CAD data along with life cycle, embodied energy and detailed climatic data to create an individual lifetime profile for a building design (Figure 7). Users are able to modify their design to explore different life cycle energy scenarios through material choice, orientation and layout.

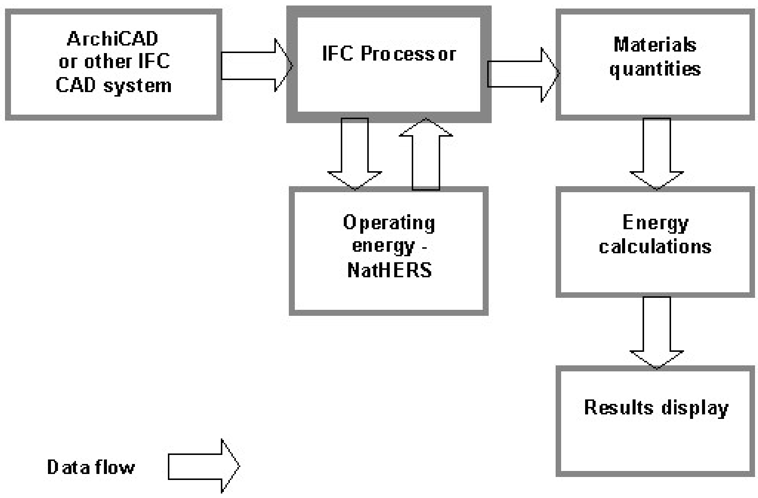

Figure 7. Australian development of the interaction of CAD designs and LCA with respect to energy (Drogemuller et al. 2002).

4 CONCLUDING REMARKS

Needs for integrated approaches are increasing in the construction and real estate sector. Purposes of integration are in common to support risky decision-making at various levels of organisations and at various phases of processes. Due to the complexity of interacting systems and requirements to manage life-cycle issues, the design processes are adopting highly digitalised practices. This means e.g. simulation and building information modelling. Physical simulation is becoming available for every-day practices and models and physical models of human behaviour are linked in R&D. The importance of reliability and risk analysis is essential in integrated approaches.

The needs of sustainable development have led to a completely new scientific approach, "sustainability science" that is characterized by integration. During the last decade, an increasing number of publications and journals is dealing with problems of integrated approaches. Although some doubts have been presented about the quality of integrated sciences, there are reasons to believe that modern ICT technologies offer possibilities to even raise the level of basic sciences parallel to the combined efforts. The needs to understand the real phenomena affecting human life and nature as well as the reliability of knowledge are drivers of high-level scientific work. This argument is valid for constructions.

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