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MODELLING THE LIFE-CYCLE OF SUSTAINABLE, LIVING BUILDINGS

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EDITORS: Rezgui Y, Zarli A, Hopfe C J

Sander van Nederveen, Dr,
Delft University of Technology
g.a.vannederveen@tudelft.nl, www.bouwprocessen.citg.tudelft.nl

Wim Gielingh, Dr,
Delft University of Technology
wgielingh@tiscali.nl, www.bouwprocessen.citg.tudelft.nl

SUMMARY: *Credit-reductions by banks, as a consequence of the global monetary crisis, will hit the construction industry for many years to come. There are however still financing opportunities for building projects that are perceived as less risky. Buildings that are not only sustainable, but also flexible and adaptive, are becoming attractive alternatives for traditional buildings. Many innovative concepts are combined in a new form of contracting, called the Living Building Concept. In this concept, buildings are continuously adapted to changing user and/or client needs in the form of Product/Service combinations. In this paper we will zoom in on the implications for building information modelling and construction ICT. Object based, parametric design technologies become more important than ever before. The new business concepts require a life-cycle modelling approach in which individual components and materials play a central role. Buildings are considered as temporary configurations of these components and materials. The functional life of buildings, which strives for higher and sustainable end-user value, becomes detached from the technical life of building components and materials, offering new opportunities for reuse, remanufacturing and recycling.*

KEYWORDS: *cradle-to-cradle, living building concept, remanufacturing, recycling, performance based building, sustainability.*

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1. INTRODUCTION

The Construction Industry is in a crisis, today even more than in the past decades. Especially the crisis on the financial markets has forced banks to reduce credits for construction projects. Not only speculative projects initiated by investors are victimized, but also socially vital projects such as for hospital buildings and housing. Large scale layoffs have become inevitable.

It may take many years before the markets recover fully. And once this will be the case, it is likely that the markets have changed. Speculative investment projects are likely to become something of the past. Such projects were initiated by banks for the creation of Collateralized Debt Obligations (CDOs) which fuelled the financial bubble that preceded the credit crunch. Given the expected stabilization or even shrinkage of population, future construction projects will be less speculative and more driven by ultimate end-user needs. Energy prices and the prices of certain base materials such as metals (steel, aluminium, copper) and plastics may rise to unprecedented levels. Due to their large energy demand in production, bricks, cement (concrete) and glass will also be substantially more expensive. Because of rising material costs, it is likely that buildings become less massive.

Material and energy prices will affect the costs of construction more than labour costs, and this will have also an impact on construction processes and building design, and, ultimately, on methods and supporting ICT tools. Business offerings that are not sustainable will not survive the crisis.

Given these considerations, we present a lifecycle model in this paper that is based on a holistic concept for construction, called the Living Building concept (De Ridder 2006, De Ridder & Vrijhoef 2007). In its most recent form it comprises and integrates several existing concepts focusing on (1) sustainability, such as the cradle-to-cradle principle, remanufacturing and the post-mass-production paradigm, (2) on new business models, such as Product-Service Systems and Performance Based Building, (3) on new financial models, such as the Terra Trade Reference Currency, and (4) on flexible, industrialised building concepts such as Open Building.

The goal of the current paper is to analyse the impact of these new developments on ICT.

This paper is structured as follows. Chapter 2 discusses the factors that will trigger business innovation in the construction industry. The Living Building Concept is an example of business innovation that provides a coherent framework. Chapter 3 compares the business process for Living Buildings with the traditional construction process. Next, chapter 4 identifies the implications for ICT. Chapter 5, finally, draws conclusions.

2. FACTORS THAT AFFECT THE FUTURE OF CONSTRUCTION

2.1 The five planetary issues

As habitants of planet Earth we are confronted with several major issues that occur more or less simultaneously:

a. depletion of natural resources, including fossil fuels

b. devastation of environmental conditions, including the impact of climate change

c. increased standard of living on emerging continents, which results in increased consumption of natural resources

d. aging of population in industrialized countries, and relative reduction of labour force

e. bankruptcy of the banking system

About 5 billion people live in emerging economies, and this number is growing rapidly. As these people strive for the same high standards of living such as enjoyed in the rich developed countries, it is likely that the consumption of natural resources, the depletion of resources and the devastation of our environment will accelerate. Although the financial crisis has led to an economic slowdown, and thus to a temporary reduction of market prices of natural resources, prices are likely to rise again to unprecedented levels once the economies recover.

Aging in the industrialized countries is another major concern. Certain regions in Europe, as well as Japan, are confronted with a shrinking population, and even more with a shrinking labour force. Until recently real estate developers could easily sell or rent any facility they built because of the growing population. But this is changing rapidly, ultimately causing vacancy of existing properties. Property development, which was so popular as a form of investment during the last decades, is likely to be replaced by a more user driven building demand in the future.

Today, most buildings are designed to meet today's user requirements and todays social, environmental and technological standards. They are in most cases built for the lowest initial costs. End-of-life consequences are usually ignored, and, as they are difficult to predict, future user demands and future social, environmental and technological standards are seen as risks in stead of opportunities.

Because of their high initial costs, built artefacts are assumed to last at least 30, possibly up to 100 years. Buildings that need to be demolished because user and other demands have changed will probably have no value at the end of their life. In fact, they may have a negative value because of the costs of demolition and the production of waste.

Hence, there is a need to think about the impact of future requirements, even though these requirements are unknown or uncertain today. Not by trying to predict the future, but by accepting change and uncertainty as a fact of life. In this line of thought, a building should not be designed as a static object, but as a process. This process should also incorporate end-of-life strategies.

2.2 The crash of the financial system.

The crash of the banking system in 2008 has caused a slowdown in construction in practically all regions on Earth. This situation may continue for many years to come (Lietaer et al 2008).

The credit crunch is caused by the fact that most debts are backed up by assets, of which real estate, such as houses, are the most popular. If a lender is not able to meet its obligation to pay rent or to pay back the loan, a bank has the right to take over the real estate, and to sell it in order to redeem the debt. However, if the asset is not easy to sell on the open market, or if its value has decreased, the bank may not be able to convert the stone (or steel, concrete or wood) into money. This happened in the US housing market since the middle of 2006 and led to a domino effect of falling banks in 2008. Although the banks were saved by national governments, they now hesitant to lend out money to construction projects of which the collateral cannot be easily sold on the open market. Also projects for which there is no immediate client - such as (speculative) real estate investment projects - may be perceived as too risky. In such cases banks may still be prepared to lend money, but at such high interest rates that the economic justification for the lender disappears.

In contrast, sustainable construction projects that are designed for disassembly and reuse of materials, and for projects of which the operational use is secure for a long period of time - for example of multi-functional facilities - may be met with reduced interest rates.

The future of the banking system is still uncertain, but the impact of the current crisis is so huge that, for many years to come, banks will be discouraged to take risks anywhere near the situation that occurred just before the crash happened. In other words: the financial systems of the future will encourage low risk, sustainable construction methods.

2.3 Product-Service Systems

In the classical view of construction, a building is a static object that meets user requirements which are specified before design and construction start. It is assumed that user requirements, and thus also building specifications, do not change afterwards. Clients who change their mind are penalized by high additional costs. Contracts protect the builder legally against clients with changing needs. The term ‘maintenance’ emphasizes the current static way of thinking, as its goal is to keep a building as much as possible in its original state.

This form of thinking will likely (and hopefully!) change during the next decades. It should be recognized that user requirements, but also social, environmental and technological requirements, change continuously. A building should not be seen any longer as a static object that meets only initial needs, and which ignores the idea that life has an end. *A building must be seen as a process,* being capable to meet changing demands.

A generic business concept that supports this line of thought is called a ‘Product Service System’, or PSS. Goedkoop et.al. (1999) define a Product Service system as "a marketable set of products and services capable of jointly fulfilling a user’s need". Key-factors of success are:

- to create value for clients, in economic sense or by adding quality and comfort,
- to customize solutions to meet specific client needs,
- to create new functions or to make unique combinations of functions,
- to decrease the threshold and risk of capital investment by sharing, leasing or renting,
- to decrease environmental load and to deliver eco-benefits,
- to respond better to changing client needs.

Product Service Systems introduce a different way of doing business and require new kinds of contractual arrangements. As providers do not earn money by selling materialized products but by selling performance (i.e. the ‘output’ of the product) a PSS has the potential to unlink environmental pressure from economic growth (Manzini, Vezzoli). The term ‘provider’ is deliberately used in order to emphasize the shift from selling goods to selling services.

An example of a product service system is offered by producers of printing and copying machines, such as Xerox, Fuji and Océ (Kerr and Ryan 2001, Steinhilper 1998). In their PSS business models the companies do not sell printing or copying *machines* but a printing or copying *function*. Clients pay for the output of a machine and for quality and reliability. The combination of product and service is designed to deliver performance. If a machine runs out of toner, it automatically orders a new cartridge which may be delivered and installed by the provider. The condition of operational machines is monitored through sensors that record the number of copies made, paper-jams, heat and/or other critical performance criteria. Before a machine breaks it can thus be repaired or replaced by a 'new', more reliable one. If the requirements of a client change, the provider replaces a machine by a new one. 'Old' machines are taken back and disassembled. The parts are remanufactured and used again for the production of new machines. This reduces waste and the costs of making completely new machines from fresh natural resources.

2.4 A Product-Service System for construction: the building becomes a process.

The Living Building concept (de Ridder 2006, de Ridder and Vrijhoef 2007, Gielingh et al 2008) can be seen as a Product Service offering for construction. An LB provider takes full Extended Lifecycle responsibility for buildings and their parts, and may even own it. The provider earns its money through the ‘output’ (i.e. the performance) that the building offers.

Providers develop portfolios of solutions for specific product/service - market combinations, such as for housing, education (schools), health care (hospitals), retail (shops, retail centres, airports), business (offices) or infrastructures (bridges, roads). Each solution consists of a building concept and a suite of services that both can be customized to specific client needs.

An LB contract aims at the delivery of maximal value for minimal costs. It does not freeze user requirements or building performance. If user requirements or external conditions change such that the building offers a sub-optimal solution, it will be changed. Goal of the LB concept is therefore to keep a building fit-for-use, not just for once, but forever. This is one the biggest differences with other integrated contracts such as DBM(FOT), which still assume fixed user requirements for a given period of time.

In order to keep clients and users happy, providers must become proactive. They should not wait until clients or users start to complain. The provider must therefore understand the processes that are facilitated by the building. User processes, social and environmental boundary conditions, as well as building performance, are continuously monitored. If any of these conditions change, the provider may adapt the building and/or service. Depending on details in the service level agreement and impact on the agreed price, the provider can do this autonomously or by mutual agreement with client and/or user.

For each modification requirement, there may be zero, one or more solutions. Each solution will have its benefits and implications. These benefits and implications are considered in a broader context: change requirements can be addressed more economically by combining them into a single solution. Decisions about modifications are thus based on a rationale, in which integral benefits are weighed against integral implications.

The whole of benefits will be called 'value', while the whole of implications will be called 'cost'. Values and costs may however not be limited to financial values and costs. Amongst the factors that can be incorporated in a value/cost model are social, cultural, environmental, ethical and esthetical values, as well risks, wellbeing and health. Not all of these can be expressed in terms of money so that the weighing of heterogeneous values and costs is subject that deserves further attention.

The difference between value and costs is called 'yield'; providers strive for optimal yield during the life of a building, and will be rewarded accordingly. The rewarding mechanism is therefore a form of performance based rewarding, in which the performance indicators are dynamic.

In order to be proactive, the provider must monitor user processes and environmental conditions. In consultation with the user(s), the provider may take the initiative to modify the building so as to prevent ill-performance. During the modification of a building, user activities should continue, preferably undisturbed.

Where current, static buildings require high investments that have to be written off and are risky if user needs change considerably over time, the components and materials that constitute a living building have an extended lifetime that may be substantially longer than any individual building. Because of the shift from building centric thinking towards component centric thinking it becomes economically feasible to realize buildings with an uncertain lifetime. Normally, buildings have to be written off over a period of at least 30 years in order to make the investment financially justifiable. In the proposed new business model focus will be on sustainable components and materials with a lifetime that may be more than 50 years, while the building of which they are part may exist, say, 5 to 20 years. Hence the risks in capital investment will decrease significantly.

In this scenario, the costs of component and building material production decreases relative to total lifecycle costs. But the number of actions or operations per unit of material will increase. This is inherent to the shift from industrialized (mass) production to service oriented business models. In current construction practice, only the initial production, manufacturing and construction costs contribute to material costs. In living buildings, materials and components are manufactured, assembled, disassembled, remanufactured, and so on, perhaps many times during their (extended) lifetime. Manual work will therefore be costly. It may be more economical to automate these processes for Living Buildings than for traditional buildings.

The envisioned process of a Living Building product/service provider is sketched in Figure 1.

The pentagon just above the centre of this diagram depicts the building lifecycle, which becomes indefinite in the envisioned approach. Two aspects of buildings are of interest: (a) their physical state – indicated by the lower red part 'building in operation' – and (b) their performance – indicated by the upper blue part. The entire pentagon forms the heart of the business of a provider: it is a combination of a product ('the hardware') and a service, which aims at offering the best value for money to a user.

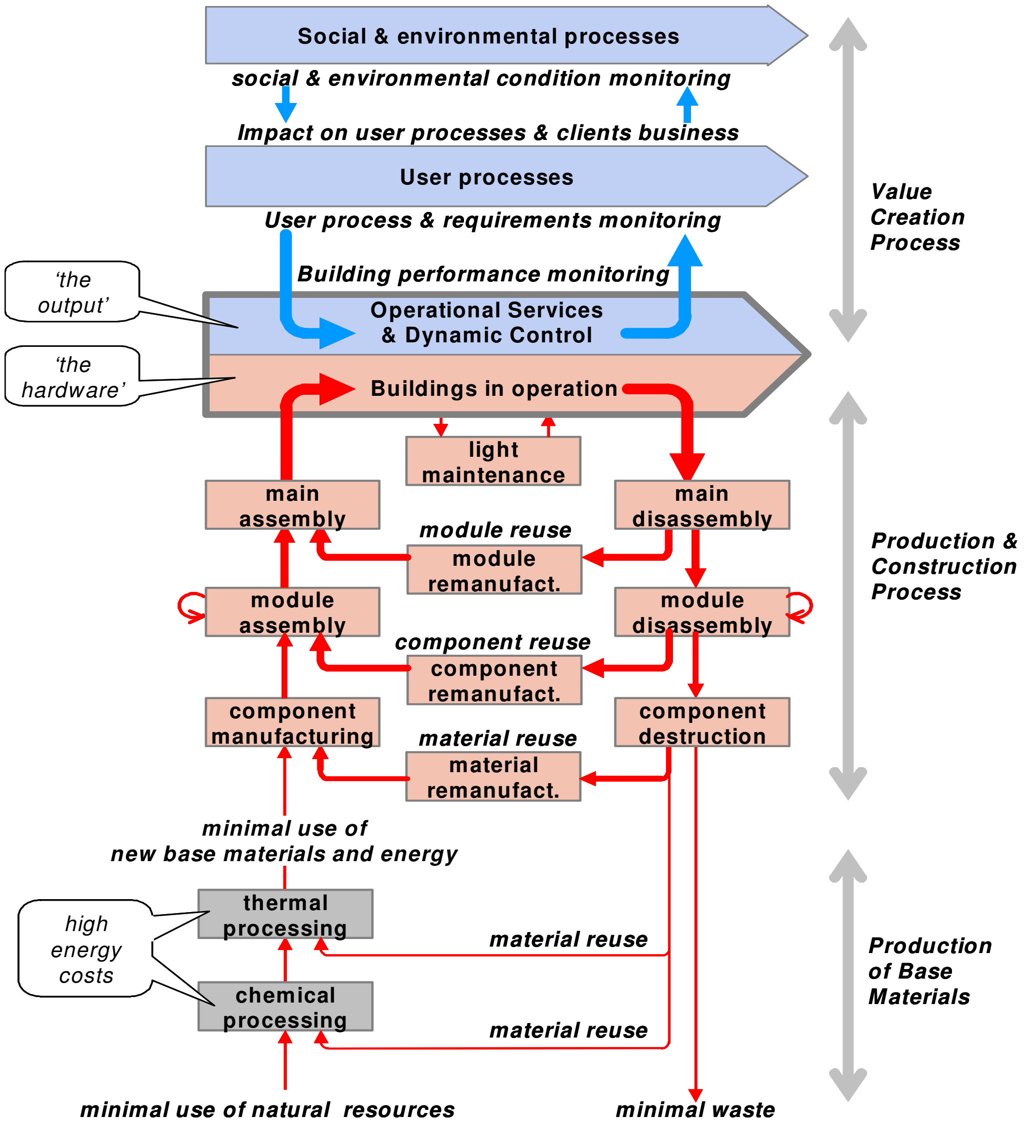

FIG. 1: The process of a Living Building provider aims at offering a dynamic solution for dynamic user, social and environmental needs. It also aims at reducing waste and the need for new base materials and energy.

The upper part of the diagram, in particular the blue arrows and boxes, shows the value creation process. It consists of the sustained monitoring of user processes and requirements, and of the sustained monitoring of social and environmental conditions. Both aspects (internal and external factors) affect user needs. Through operational services, maintenance and building modification, the building is kept fit-for-use.

The lower half of this diagram, highlighted with red arrows, depicts the physical lifecycle of building components and materials. The lower left part shows, from bottom to top, the construction process. The shown process starts with the production of raw materials, base materials and components, and, via the assembly of modules and (sub)systems, it finishes with the building as a whole. The production of base materials is normally not considered to be part of constriction.

In case changes of the building are needed during its operational life, the building will be partially disassembled and re-assembled. In order to avoid excessive waste, removed modules may be re-used for assembly in the same or another building. If modules cannot be re-used as a whole, they will disassembled into components. Disassembly can be drastically simplified if fixtures of components and modules are designed for that purpose. Further, given the fact that vitalization may take place in a fully operational building, main disassembly and re-assembly should be designed such that ongoing activities in the building can continue with little or no disturbance.

2.5 Maintain, reuse, remanufacture, recycle or waste?

A traditional building can be seen as a *materialized* solution for user needs that existed before it was constructed. If user needs change drastically, the building may have to be declared as being useless, so that it may have to be demolished. This attitude causes construction to be a large producer of waste. Not only the waste may be a problem, it causes also an exhaustion of natural resources.

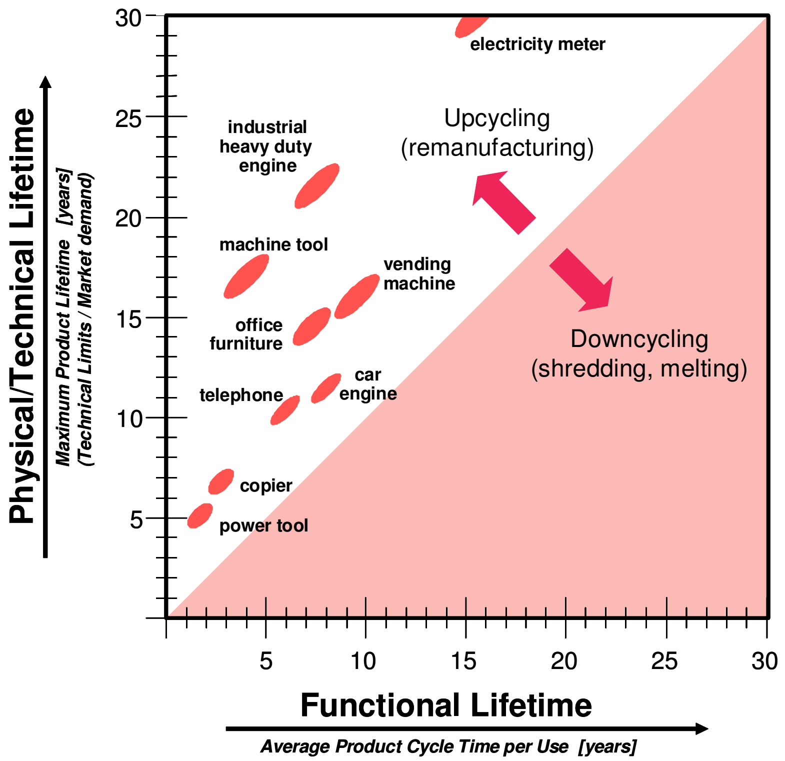

FIG.2: If the physical or technical lifetime of products or its components is longer than its functional life, there is a case for remanufacturing (or 'upcycling'). Diagram derived from (Steinhilper 98).

However, systems that are not any longer useful for one building, but which are by themselves technically sound and useful, may be re-installed in another building. And if systems cannot be re-used as such, they can be disassembled into elementary components which are remanufactured into new components. The technology for remanufacturing is already well-developed in the automotive industry (Steinhilper 1998). Remanufacturing does not only save materials and avoids waste, but it saves also huge amounts of energy that would otherwise be needed for scrapping and melting. In automotive, remanufacturing saves around 90% of the energy that would otherwise be needed for the production of new components. Finally, if components are not suited for remanufacturing, the materials from which they are made may still be suited for recycling.

Figure 2 shows a graph of the physical or technical lifetime of products/components versus their functional lifetime (Steinhilper 1998). If the first is longer than the second, there may be a business case for remanufacturing, e.g. cleaning, repairing, resurfacing and/or repainting of components after partial or complete disassembly and before reassembly. This process is also called *upcycling* because the reused systems or components become 'as good as new'.

A decision model for finding the optimum between maintenance, reuse, remanufacturing, recycling or waste has been developed by Tomiyama (Tomiyama 1997, Umeda et al 2000) for the mechanical industry and is called the Post-Mass-Production-Paradigm (PMPP).

Reuse and remanufacture strategies can already be taken into account in the design phase, and complies with the cradle-to-cradle concept such as described by McDonough & Braungart (2002). It has implications for the use of materials and the way in which components are joined (Durmisevic and Brouwer, 2002)

An analysis of 20 Australian schools done by Ding (2007) revealed that the amount of energy needed to produce, maintain and demolish a school is about the same as 37 years of operational energy (heating, cooling, electricity). The selection of materials has therefore a major impact on the overall energy-consumption of a building. Commonly used materials such as steel, glass, cement (which represents about 16% of the volume of concrete) and brick require very high temperatures in production; temperatures that may only be reached through the burning of hydrocarbons. Hence, the production of these materials contributes significantly to the global CO_2 problem. This can be saved by reuse and remanufacturing.

2.6 The expression and modelling of value

One of the toughest problems in decision making is the fact that several incomparable values and costs have to be weighed against each other. The costs of making a building are not just financial. The production of a building may also negatively affect the environment, such as through the production of CO_2 and the depletion of natural resources. The may also reduce natural territory and affect cultural heritage, such as landscape. Of course, these costs have to counter weigh benefits, such as financial profits through commercial exploitation, social benefits, and perhaps even environmental benefits ('green buildings' that replace older buildings). Not only the initial benefits/costs are relevant, but also the long term impact.

The difficulty here is how values and costs should be expressed, in order to make fair decisions possible. Today, most decisions in construction are based on lowest initial financial costs. Not on lifecycle costs, and not on the costs of demolition. Non-financial costs are hardly taken into account, other then through permission granting procedures. Once permission is given, it is usually valid for the entire life of the building.

Time is another important factor. The financial and environmental costs to operate, maintain and demolish a building can be very high. But decision makers are inclined to focus mainly on initial costs. This is caused by a factor that distorts lifecycle costing models: *interest*. If one puts an amount of money on a bank account, this amount will grow over time due the effect of compound interest. It encourages investors to postpone investments that give no short term return. With an interest rate of 5%, an amount of money will quadruple in less than 30 years, and grows to its tenfold in 50 years time. Hence, even if the costs of demolition would be as high as the costs of construction, and if these costs would be reserved in a construction budget for a building with an estimated lifetime of 50 years, they would weigh for only 10% in the initial budget. This is why investors want to limit investments in green technology to at most 10% of the initial budget.

This way of reasoning, which is quite normal in lifecycle costing calculations, is actually incorrect. This is because inflation is not taken into account. Inflation is considered as an unknown and unpredictable factor, and is therefore usually omitted. But inflation can actually be modelled and predicted, if the main cost factors for buildings are taken into account. The three dominant cost factors are (1) human labour, (2) energy and (3) base materials (resource materials) – not necessarily in this order. Given the fact that in many western countries the population is expected to stabilize in the next decades, the costs of human labour will also stabilize. Regardless the growth of money on a bank account, the number of hours that can be bought with that money will remain roughly the same over time. Hence, money that is spent on human labour will retain its value over time. Inflation will therefore be approximately the same as compound interest. Due to the depletion of natural resources, including fossil fuels, over time, it may even be that the inflation for energy and base materials will be higher than compound interest. No matter how fast money 'grows' on a bank account, the amount of energy and the amount of base materials that one can buy in the future will probably grow less (or even shrink) relative to global population growth. This will be reflected by continuously rising market prices for commodities. The idea that we do not have to think about demolition and possible reuse of materials because these costs or values would be marginal relative to initial construction costs is thus false.

Current money systems do not make the issue of sustained value visible. This is also one of the causes of the current financial crisis. During the last two decades the financial markets grew much faster than the real economy. For instance, in the Netherlands, banks, insurance companies, pension funds and stock markets grew 4 to 10 times faster than the gross domestic product during this period (Bos 2008). As the real value of money is determined by what one can buy with it, it is clear that we were witnessing the growth of a financial bubble.

The Terra Trade Reference Currency™ (Kiuchi 2004) is designed to solve the described problem. The Terra is not a real currency, but is proposed as a reference currency against which the real value of other currencies can be estimated. It is not sensitive to inflation or deflation because it is interest-free and directly coupled to the market value of commodities, services and environmental factors such as CO_2. The Terra is not yet operational today; it is merely a concept. But this concept may become a future solution for the expression and valuation of heterogeneous values in complex decision making processes.

2.7 Living Building pilots and comparable developments

In the Netherlands, several pilot projects for living buildings were recently initiated. Of these, the pilot for the Gemini hospital of Den Helder, a small town on the northern tip of the province of North Holland, is in the most advanced stage. Hospital buildings were up to now owned by the government, but from 2012 on they will be owned by the hospital organizations themselves. The Gemini hospital serves the town and its immediate surroundings, as well as island Texel further to the north. Due to changes in medical treatments, as well as the trend to minimize the overnight stay of patients, the current building is used in a way for which it was not designed.

FIG. 3: A new hospital in Den Helder will be realized as a 'Living Hospital', replacing the current building.

Hence, there is a need for a new building. But the risks of building and exploiting it are conceived as very high. It may be, for instance, that certain treatments can be done more effectively in another hospital in the region. It may also be that the required number of beds for the overnight stay of patients, which is decreasing steadily, will decrease further. It may even be that, within ten years time, it will be concluded that the entire hospital has to be closed for efficiency reasons. These uncertainties make the investment in a new building extremely risky. This formed the reason to contract the project out as a 'Living Hospital'. Apart from the principles outlined in this chapter, the hospital will be designed, built and exploited as a multi-functional and even trans-functional building. This means in practice that some parts of the building will be owned and operated by a hotel- and restaurant-operator, and other parts by a pharmacy, a fitness centre and an office rental organization. This form of collaboration results in mutual benefits and reduces the risks for all parties involved. If the building complex ceases to be operated as a hospital, it may continue its life as a hotel, restaurant, fitness centre, pharmacy, office building and health centre.

Apart from concrete Living Building pilots, there are many other developments in construction moving in the same direction. The German construction company Cadolto is specialized in the building and rental of real estate that may be subject to rapid changes, including hospitals, centres for the care of elderly people, cleanrooms and laboratory buildings. It provides its services through a highly modular building concept and predefined solutions from which a client can choose.

FIG.4: The new headquarters of the World Wildlife Fund in Zeist, The Netherlands, is claimed to be CO_2 neutral. It is based on the skeleton of an existing office building and is largely built from reused materials.

As an another example, the German/Dutch architect Thomas Rau designs and realises new buildings by reusing materials from demolished buildings, thus closing the material lifecycle; see figure 4. In other countries, comparable developments can be witnessed.

Further to this, it is important to note that the European Parliament has accepted a directive on waste elimination which states that by 2020 measures shall be taken by all member states such that 70% of non-hazardous and non-natural construction materials will be reused or recycled (European Parliament 2008)

These developments make clear that, when we talk about 'lifecycle', it should not be limited to the building as a whole. In fact, every part of a building has its own lifecycle: it may be the same as the building of which it is part, but it may also be shorter or longer. In these cases it is important to obtain an understanding of the past, present and future of building materials and components. Further, design for reuse does not start with an empty sheet of paper, but with existing buildings and readily available components and materials.

3. PROCESS INNOVATION REQUIRED FOR SUSTAINABLE CONSTRUCTION

The question is now what the implications of these developments are for construction ICT and Building Information Modelling. Can information technology help to make the vision of 'Living Buildings' feasible? Before answering these questions, the most fundamental differences between the traditional building process and the envisioned future process will be discussed.

3.1 The traditional process

Figure 5 presents an IDEF0 (or SADT) model of the traditional process, with the purpose to highlight differences with the envisioned new process. Information flows are depicted by blue arrows, and material flows by red arrows. This model is of course simplified for the purpose of this paper.

In this traditional process, user needs have to be specified in the form of usage requirements. These are addressed by a design, which forms subsequently the basis for the construction process. We may state that the original user requirements are translated in the design by requirements for a building, which are subsequently translated into requirements for materials and components. While the building 'materializes', the original user requirements disappear to the background. It is assumed that these requirements never change. Only if they don't change, it must be assumed – provided that the translation of user requirements 'into stone' is done well - that the building will perform well. However, if the user requirements do change, the building will most probably underperform. This may ultimately lead to a usage for which the building was never intended, or at the end, in demolition.

The material flow in this process (red arrows) starts with the excavation and production of fresh (raw) materials. These are converted into building materials and components, which are subsequently assembled into a building.

After demolition, the building ends up as waste. Clearly, this process is not sustainable. It requires also a financial write-off of the building as a function of time.

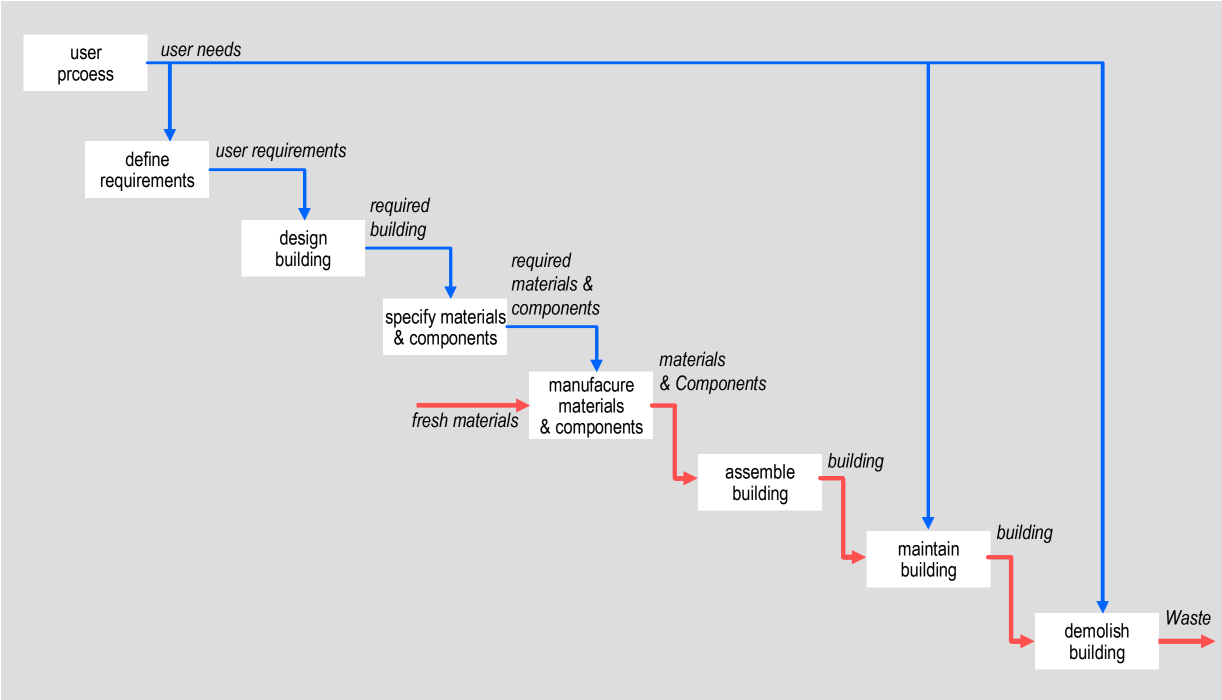

FIG. 5: IDEF0 diagram of the traditional process in construction.

3.2 The process of a Product Service System for sustainable construction

An IDEF0 diagram of the envisioned PSS for construction is shown in figure 6. The idea that user needs have to be recorded formally as requirements is dropped in this process. It is quite difficult for users to define their needs. Often, users want to be surprised by new offerings on the market. Further, the only certainty we have is that user needs will change anyway. We assume in this process that the provider of a Product-Service combination understands the user processes and thus has a generic understanding of needs. Only specific demands and specific aspects of user activities need to be known before the design and construction processes start.

To ensure that the building is ‘fit-for-use’ and remains ‘fit-for-use’, both the user processes and the building are being monitored. Also social and environmental conditions are being monitored, although this is not shown in the diagram. This is needed because the perceived building performance depends not only on the building itself, but also on usage, social conditions and environmental conditions (Säteri 2004).

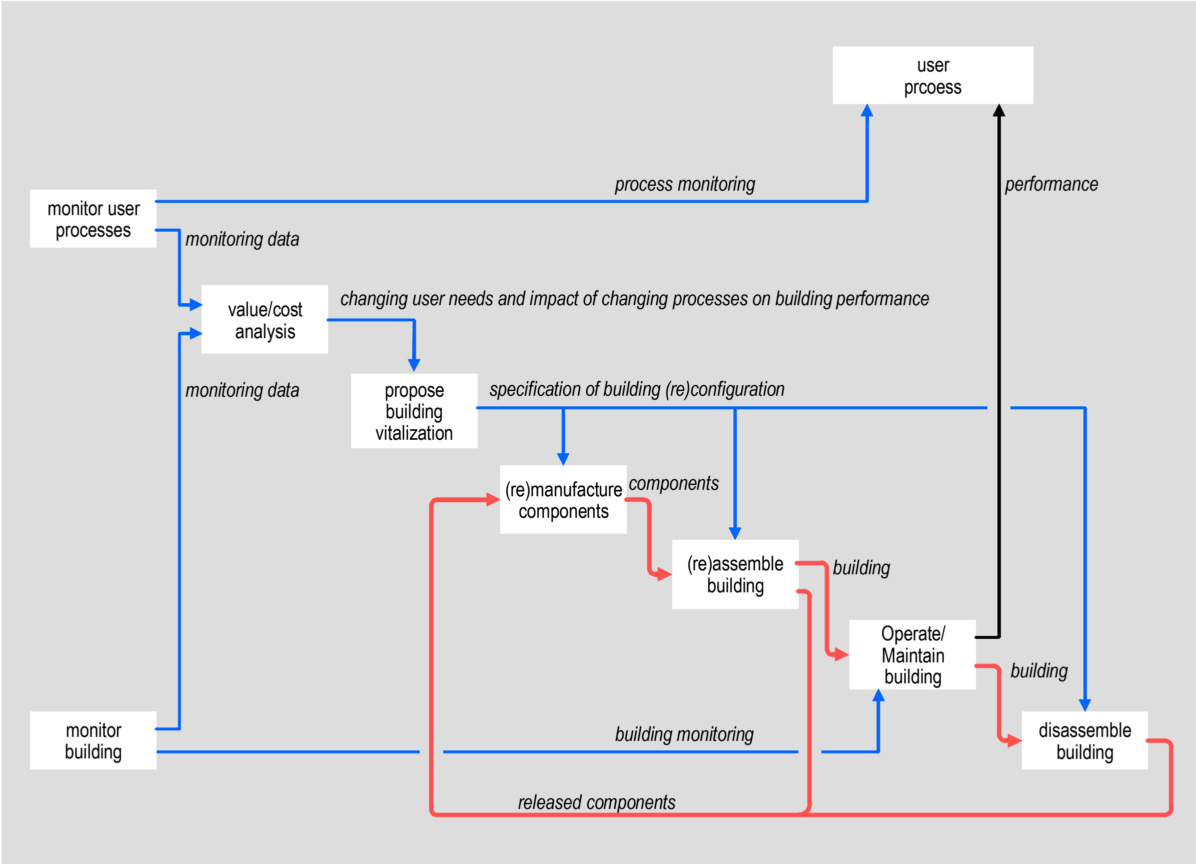

FIG.6: IDEF0 diagram of the envisioned future process in construction.

The monitoring data form input for an evaluation activity, which takes place at regular intervals, and which weighs the actual value of the building against costs. Value and cost may not be restricted to financial value and cost: also non-financial factors may play a role here. Based on the outcome of this process, the provider may propose to change the building. Such a change is called 'vitalization' because its purpose is to keep the building vital and 'fit-for-use', not just to keep it 'fit-for-purpose' through maintenance. This is because usage may deviate from purpose after a while. If agreed by all relevant stakeholders, the building will be modified.

Such modifications may cause redundant components to be removed from the building. If these components are still useful elsewhere, they are collected and – if necessary - remanufactured. Remanufacturing can be as simple as cleaning, but it may also include surface treatments (removal of old coating layers and/or scratches, as well as repainting), size reduction or other modifications. If there is no expected future for the components as such, the materials from which they are made can still be reused by milling, pulverization, shredding, melting or chemical processing. As already discussed in chapter 2.4, 'upcycling', which is reuse without melting and/or chemical processing, is preferred because it retains value and requires much less energy than 'recycling' or 'downcycling'.

In ultimate form, all components and materials that are released from a building could be reused in new construction or vitalization processes, thus closing the material feedback cycle. This ideal situation is shown in figure 6. In practice it will of course be difficult to avoid the use of fresh materials and to avoid the production of waste, certainly in the transition stage from current practices to the envisioned new practice. Figure 6 also doesn't show the initial construction process, as this can be considered as a special case of 'vitalization'. Once there is a proper basis of buildings available, the process will look more and more like the one that is shown here.

Reuse of components and/or materials requires that buildings can be disassembled easily, preferably with little or no damage. Designers should already take notice of the disassembly process and of the possibility to reuse components or materials with minimal energy or chemical processing.

The client is not mentioned in this diagram, nor in the preceeding one. In construction, the client can be the same as the user, but very often it is not. Whoever the client is, he or she will benefit from happy users; not just at the start of the life of a building, but as long as possible.

One might question whether the envisioned process will be implemented in the form that is presented here. First, it should be noted that closure of the material processing loop, such as shown by the red arrows in figure 6, is probably unavoidable. Seventy percent reuse of materials will be enforced by European law within a decade from now, and environmentally conscious clients may demand it much sooner. Further, it must be realized that alrwady more than half the work done in construction is on existing buildings (i.e building renovation). This percentage wil increase further in the years to come. Several contractors and engineering firms are investigating new forms of business as a result of the increasing popularity of integrated (service oriented) contracts and performance based rewarding schemes. Most of these contracts are still based on fixed targets and fixed performance indicators, but it is likely that a more dynamic business model will be preferred in the future.

4. IMPLICATIONS FOR BUILDING INFORMATION MODELLING AND CONSTRUCTION ICT

The implications of the envisioned new process on Building Information Modelling and ICT for construction will be discussed here for four main themes: Standardization, Performance Monitoring Technology, new design methods and Computer Aided Design, and Product Lifecycle Modelling.

4.1 Reduced need for standards

In the envisioned business model, the Product-Service provider of Living Buildings takes full lifecycle responsibility for the buildings. This implies that the provider can also use ICT systems that support the entire lifecycle. The problem of fragmentation, which is so characteristic for the construction industry today, will at least partially disappear. The only need for the exchange or sharing of data with other organizations is with authorities for permission granting and with suppliers. Hence, the need for – and dependency on – standards for product data exchange will also reduce. This has the advantage that any problems that occur with data sharing or exchange are also avoided.

The trend to take full lifecycle responsibility in construction is widely noticeable. In the plant construction sector, for instance, there are more and more companies that offer integrated engineering, construction management and maintenance management services. They do this more effectively than in the case of split responsibilities, thanks to the usage of advanced nD CAD and PLM systems. The number of integrated contracts, such as DBM(OFT), grows rapidly in construction.

4.2 Monitoring technology: from data to knowledge

The proposed new business process, in which the provider takes a proactive role, requires extensive monitoring of building condition, user processes, environmental conditions, and social factors. These factors contribute to the perception of building performance.

The data that are produced by monitoring systems will be useful on four levels with a different time horizon: (a) operation, (b) servicing, (c) vitalization, and (d) PSS strategy.

Operation

Time horizon: seconds to minutes. This level affects the operational state of a building. The perceived quality of the inner climate in a building, for instance, depends on physical parameters such as temperature, humidity, airflow, the chemical composition of air, and the level of polluting particles. But a room in which inhabitants are active, such as a sports room, may require a lower temperature and/or lower humidity than a room in which people are passive. If a room has multiple purposes, conditions may have to change accordingly. Perceived air quality may also depend on the number of occupants of a room, which may vary over time. An 'intelligent building' may react automatically on different circumstances, trying to keep air qualitity on the same, constant level. But, as stated above, if user activities change, the same physical condition may not be perceived as the same quality level for its occupants.

Servicing

Time horizon: hours to weeks. The need for servicing, such as cleaning or maintenance, may depend on the physical state and usage of a building. Rooms that are more intensively used, and which are used for activities that cause pollution, may require more frequent cleaning than other rooms.

Vitalization

Time horizon: months. This level addresses modification of the building. The required capacity of a building as a whole may vary over time. The number of classrooms of a school, for instance, may depend on demographic changes of the municipality that it serves. The number of beds in a hospital may depend on demographic aspects too (f.e. the percentage of elderly people), but also on new medical techniques (trend towards policlinical treatments) and organizational changes (mergers with other hospitals, new specializations, etc.).

Technological and climatological changes may affect also the technology used in a building. There is a trend to make buildings more ‘intelligent’, thus requiring the installation of new monitoring systems. As many buildings in Europe and Asia are not equipped for cooling in hot summers, climate change may force building operators to install air conditioning systems in existing buildings.

Fashion is another factor that may motivate vitalization. Shops already change their interior every few years. But this trend may be taken over by building operators in other sectors, in order to compete on the open market. In many countries, former public organizations have become commercial organizations. And once they have to compete, they may also want to offer their clients or guests modern, high standard hospitality.

PSS Strategy

Time horizon: one or more years. The strategic level concerns changes in the Product-Service portfolio of a provider. It is not concerned with individual buildings, but with the market(s) as a whole. Trends in user demands, new societal demands, new technologies and new materials may require changes in the offering.

Figure 7 shows two examples where measured conditions are translated into perceived building performance. The examples given show that monitoring technology should not be restricted to the building itself, but also to the usage of the building and on external factors that affect perceived performance. Relevant data may come from different sources. They have to be sampled at different intervals, and be made available in a useful form.

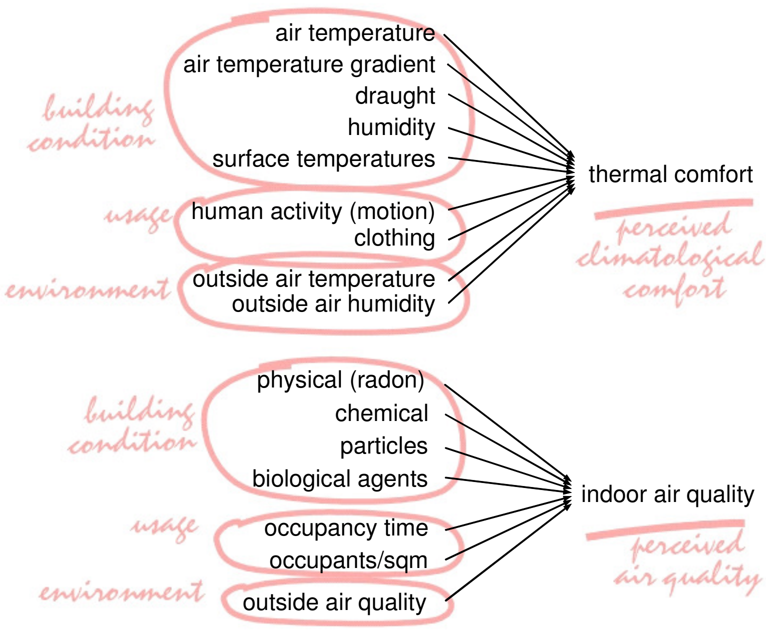

FIG. 7: Two examples of the need to monitor room condition, room usage and environment for the determination of perceived room performance.

This shown information can be relevant for the operational level (i.e. the control of heating or air-conditioning systems) but also for building vitalization (response to changing usage of the building, or to changing weather conditions) and new PSS strategies (striving for higher comfort levels using new technologies). If a provider is rewarded for the delivery of performance, it is of importance that relevant factors are measured and weighed against each other.

From an ICT perspective it means that the raw data has to be converted into a useful form, and be made available to either a building control system on the operational level; to a building maintenance or facility management system at the servicing level; to design, planning and decision management systems at the vitalization level; and to decision management and design systems at the strategic level.

The data can also be important for performance measurement, in particular if the provider is being rewarded for performance. More details about performance based contracting strategies can be found in the deliverables of the international Pebbu project (Szigeti and Davis 2005; Foliente 2005) and the work of CIB TG42 (Sateri 2004).

As stated, it is needed to convert raw measured data into useful data, and to make these available in useful form for each level. An architecture for implementation of these principles was developed for a huge Design-Build-Maintain project of 29 gas production plants in the Netherlands, see figure 8 (from Gielingh 2005). In this architecture, vitalization and strategic improvement are combined on a single level.

Three different sources of data acquisition are recognized (figure 8 top): (a) automated data acquisition, using electronic monitoring devices (sensors); (b) non-automated data acquisition, coming from human inspection reporting; and (c) knowledge recording, which consists of all other forms in which lessons learned or user satisfaction is recorded.

The data that are acquired with the first two methods are raw and need to be processed in order to be useful. They are stored in a short term data collection 'database', analysed in real time, and be made available for operational purposes. Analysis and diagnostics can be supported by rule based inference. In the case of gas plants, it is of utmost importance that data from sensors are analysed and interpreted correctly in order to avoid hazards. The well known Piper Alpha disaster (wikipedia 2009) was caused by the fact that operators did not have timely access to reliable data, could not conclude rapidly enough what the cause was of multiple anomalies occurring simultaneously, and were not able to access relevant manuals on time. The proposed technology should avoid this.

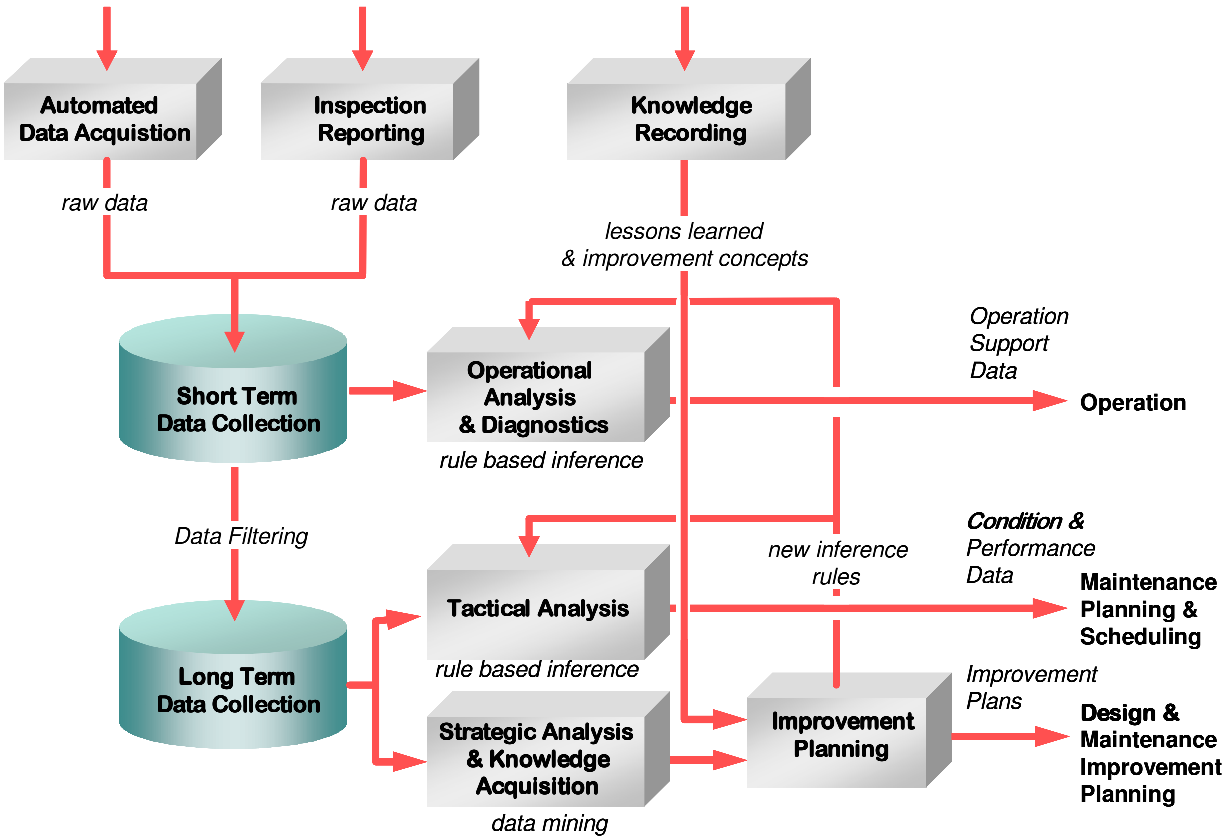

FIG. 8: An architecture for the acquisition and processing of monitoring data..

As the short term data collection can be huge, it is filtered or reworked to become useful for the services, vitalization and strategy levels. Data about the condition of equipment can be used for the planning and scheduling of maintenance. This supports a condition based maintenance strategy. Again, this type of data analysis can be automated using rule based inference. The available pool of data can also be a rich source for strategic analysis and improvement planning of individual buildings (vitalization) or of the product-service combination as a whole. Amongst others, use can be made of data mining technology. Some of the applications on the strategic level are the improvement of services, the buildings systems, the monitoring technology and the software needed for automated inference. Depending on the type of building, emphasis may shift from one level to the other, but the key principles will remain roughly the same.

4.3 Computer Aided Design

The envisioned new way of working has considerable consequences for the design process as well for the tools used in design.

4.3.1 Design for disassembly and reuse

In traditional design and construction processes, it is assumed that building components have a lifetime that is, at most, the same as the building of which they are part. If components have a shorter lifetime they will be repaired or replaced by new ones during maintenance or renovation. It is quite common that redundant components or the building as a whole will be demolished and trashed. Most building materials today end up as landfill. If they are recycled, it will be at the cost of huge amounts of energy. Given the rising prices of energy, there is a risk that material recycling will become too expensive in the future. Hence, there is a case for the extension of the lifetime of building materials and components beyond their initial functional life. This requires a rethinking of the building design, such that components are not just suited for initial usage, but also for future usage.

Moreover, the designer has to consider the possibility to disassemble the building, such that components can be released at little cost and with little or no damage (Durmisevic 2006). Further, if the components can be reused, it is likely that they need some form of rework before they look ‘as good as new’. The implications of rework – which is called *remanufacturing* – is something that needs to be considered in advance.

4.3.2 Design by configuration

Then, once reusable components become available, a new form of design practice will start: the design of buildings using available components. In stead of designing a building from scratch, a designer may look at readily available components. Once the number of such components increases, design becomes a process of component configuration. It is not any longer a predominant top-down problem-solving process, but also – concurrently - a bottom-up solution-provision process. It is expected that the reuse of components leads to a drastic cost reduction and a reduction of CO_2 emissions due to savings on material and energy costs.

4.3.3 Design for renovation and vitalization

Thirdly, future design practices will increasingly concern the modification of existing buildings. The designer does not start with a ‘blanc sheet of paper’ (or an empty modelling space in the case of modern nD design methods) but with an existing reality. It would be ideal if the designer cold use the design or building model of the existing object as a basis, but this will not be the case on the short term. Further, even if such models would be available, it is questionable whether they represent the actual situation on site accurately. The shape and configuration of the existing building may first have to be measured. Advanced 3D scanning methods at the scale of buildings are vital for this process, but the accuracy of laser scanners that can cover entire buildings may not be sufficient at present. Algorithms for the reconstruction of geometry from point clouds are also required.

4.3.4 Parametric Design

Buildings that are suited for change and modification are likely to be based on a modular system. Hence, it makes sense to design them with the help of a parametric design tool that uses a library of generic, parametrically defined components. Parametric design should not be restricted to geometry, but should also cover other relevant knowledge, including knowledge about processes such as assembly and disassembly, and the tools needed for these processes. nD modelling becomes an important prerequisite for the representation of different stages in the lifecycle such construction or vitalization.

4.4 Product Lifecycle Management

4.4.1 From building centric to component centric PLM

The most important change in Product Lifecycle Management will be the shift from Building Centric thinking to Component (and Material) centric thinking. Components and materials will have a lifecycle that may differ significantly from the building of which they are part, and which may be substantially longer. It may therefore be needed to track the history of components.

This shift in thinking can be somewhat compared with the lifecycle modelling of Lego™ bricks: these bricks can be used to make many different objects, and have a lifetime which is much longer than the objects of which they are part. For very elementary components lifecycle tracking may not seem to be relevant, but the challenge of working with 'living buildings' is to reuse components, elements or systems on a high structural level. Umeda et al (2000) describe a very interesting case for the redesign of refrigerators, in order to make components and (sub) systems reusable. They have analysed the lifetime of various components and materials that comprise a refrigerator, and propose to assemble the most sustainable ones into one or more modules. Once the refrigerator terminates its life, these valuable and reusable modules can then simply be taken out.

4.4.2 From lean to clean: rethinking logistics

The concept of reuse has a fundamental impact on logistics. Several decades ago the Toyota Motor Company™ introduced lean manufacturing. This successful concept has been copied since then by many companies in various industries. One of the fundamental principles in Lean Production is to remove 'waste activities' from a production process. An example of such a waste activity is the storage of components during the product assembly process. Intermediate storage is not needed if the time of delivery coincides with the time of assembly. This principle is called Just-in-Time (JIT) delivery.

In the new business model, the production of base materials and components from fresh natural resources is seen as 'waste'. Also the recycling of materials is a form of waste because of the huge amounts of energy required for shredding and/or melting. These processes can be avoided be reusing components or materials. As the time of disassembly and remanufacturing may differ from the time of reassembly, intermediate storage of components may be required. So, an activity that was seen as 'waste' in the Lean manufacturing paradigm, may become 'value added' in the new paradigm.

4.4.3 Market places for used components

In order to improve the cycle time for the reuse of components or materials, it may be valuable to trade them via a virtual market place. Remotely comparable market places already exist for consumer products, of which e-Bay™ is the most well-known. Market places for used and/or remanufactured parts of cars also exist today, mostly on a national level. For reusable building components and materials they do not yet exist. There will be a need for intelligent search engines, such that the CAD system that is used by a designer can make automatic suggestions for the use of components or materials which are available on the electronic market. Please note that this concept will also reverse the procurement process: where procurement managers normally prescribe what they need so that suppliers have to respond, reverse procurement offers an overview of relatively inexpensive building materials that are readily available so that designers need to find out how such materials can be used effectively in the design. While the designer is doing this, he must be able to put a claim on these materials in order to avoid that they will be sold before a decision is made.

5. CONCLUSIONS AND FUTURE WORK

This paper presents a vision of sustainable construction methods, supported by an innovative business model and performance based rewarding schemes. The differences between the old and new business processes are sketched, including their implications for ICT and Building Information Modelling. A few pilots for this new way of working have been initiated, and reference is made to commercial initiatives that seem to head in the same direction.

The concepts of product-service systems for construction, performance based rewarding, and the reuse and remanufacturing of components have been analysed in the context of the Living Building Concept.

Performance monitoring becomes an essential aspect of this new approach, and monitoring data need to be processed for use on four distinct levels: operation, servicing, vitalization, and PSS Strategy. The implications of these concepts for building information modelling and construction ICT have been discussed. Providers that offer full lifecycle support can use ICT systems that support the entire lifecycle, without the need for data transaction. These makes these providers less dependent on the existence of standards. Transactions may only be needed for permission granting and for collaborative purposes with suppliers.

Subjects that need further exploration are:

(a) Lifecycle Costing modelling, as current models insufficiently take the impact of inflation into account and require rethinking in the light of a stable or shrinking labour force and the depletion of natural resources;

(b) Modelling and expression of heterogeneous values and costs for decision making;

(c) Transition from the reactive, requirement based process of design, construct and maintain, towards a proactive, monitoring based process of design, vitalization and reuse;

(d) Development of advanced monitoring systems, based on automated and non-automated forms of data acquisition, as well as automated analysis and diagnostics of these data, in order to support the operation, servicing and vitalization of buildings, as well as the strategic improvement of Product-Service portfolio's;

(e) New design methods, such as design for disassembly and reuse, design by configuration, and design for renovation and vitalization, to be supported by advanced parametric nD modelling systems;

(f) Lifetime extension of components and materials as part of rapidly changing 'living' buildings, thus shifting focus from building centric PLM towards component and material centric PLM;

(g) Electronic market places for the trading of used components and materials, as well as new logistic processes in support of the reuse of components and materials.

6. REFERENCES

Bos, W. (2008); *Nota over de toestand van 's rijks financiën*; Netherlands Ministry of Finance.

Ding, G.K.C. (2007) *Lifecycle energy assessment of Australian secondary schools*; Building Research and Information, 35(5) 487-500.

Durmisevic, E., Brouwer, J.(2002) ; *Dynamic versus Static Building Structures*. In: M Sun et al (eds.); 2nd international postgraduate research conference in the built and human environment; Salford, p. 484-499.

Durmisevic, E (2006); *Transformable Building Structures - Design for disassembly as a way to introduce sustainable engineering to building design & construction* (dissertation); Delft, ISBN: 90-9020341-9.

European Parliament (2008); *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste; Article 11 (Re-use and Recycling), paragraph 2b*; Official Journal of the European Union, 22.11.2008, L312 page 13

Foliente, G. (2005) *Performance Based Building R&D Roadmap*; International Council for Research and Innovation in Building and Construction Development (CIB), Rotterdam, ISBN 90-6363-048-4. Available at www.pebbu.nl.

Gielingh W., (2005). *Improving the performance of construction by the acquisition, organization and use of knowledge.* Delft. ISBN 90-810001-1-X.

Gielingh et al (2008), *Business Innovation in Construction through Value Oriented Product/Service Offerings for Living Buildings*, proceedings I3CON Conference, Loughborough University, May.

Goedkoop, M., et al (1999); *Product Service systems, Ecological and Economic Basics*. Report for the Dutch ministries of Environment (VROM) and Economic Affairs (EZ).

Kerr, R. (2001), *Eco-efficiency gains from remanufacturing - A case study of photocopier remanufacturing at Fuji Xerox, Australia*; Journal of Cleaner Production 9 (2001) 75–81.

Kiuchi, T. (2004); *The Terra TRC White Paper*. Available at www.terratrc.org

Lietaer et. al. (2008), *White Paper on the Options for Managing Systemic Bank Crises*. Available at www.lietaer.com

Manzini, E., and Vezzoli, C.; *Product-Service Systems and Sustainability*; UNEP, Paris, ISBN:92-807-2206-9.

McDonough, W., Braungart, M. (2002), *Cradle To Cradle, Remaking the Way We Make Things*, North Point Press, 2002.

Ridder, H. de (2006), *Het Living Building Concept*, PSIBouw, Gouda, ISBN-10: 90.78572-01-9.

Ridder, H. de and Vrijhoef, R. (2007) "*From demand-driven supply towards supply-driven demand in construction*". In Hughes, W. (ed.) Proceedings CME25 Conference. 16-18 July 2007, University of Reading, UK. Proceedings on CD-ROM.

Säteri, J. (ed.) (2004); *Performance Criteria for Buildings for Health and Comfort*; ISIAQ CIB Task Group TG 42.

Steinhilper, R. (1998). *Remanufacturing, The Ultimate Form of Recycling*; Stuttgart. ISBN 3-8167-5216-0.

Szigeti, F., Davis, G. (2005). *Performance Based Building: Conceptual Framework.* International Council for Research and Innovation in Building and Construction - Development Foundation. ISBN 90-6363-051-4.

Tomiyama, T. (1997) *A manufacturing paradigm towards the 21st century*; Integrated Computer Aided Engineering 4 (1997) 159–178.

Umeda, Y.; Nonomura, A.; Tomiyama, T. (2000). *Study on lifecycle design for the post mass production paradigm*; in: Artificial Intelligence for Engineering Design, Analysis and Manufacturing (2000), 14, 149–161.

Wikipedia (2009); http://en.wikipedia.org/wiki/Piper_Alpha.