Application of the Cradle to Cradle paradigm to a housing unit in Switzerland: Findings from a prototype design

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ABSTRACT: The Cradle to Cradle (C2C) paradigm is emerging as an important regenerative design approach. C2C is aiming to create a positive footprint of the built environment, beyond carbon neutrality. However, there are very few studies that address the application of the C2C concept in building design. More importantly, there is hardly any documentation processes on methods or tools currently being used to design and evaluate C2C buildings. Therefore, the purpose of this paper is to design, model and assess a C2C building prototype with a focus on energy and materials. The research methodology is based on literature review, case study design and performance (energy/materials) evaluation (DesignBuilder/SimaPro). The paper articulates the values, principles and goals of the C2C paradigm and translates them through the prototype design in the Swiss context. The results of the prototype design point to a 74% independence from non-renewable energy resources, compensating the operating and embodied energy during the building's life. On the other hand only 8% of the building materials were totally recyclable according to the C2C principles. The design process delivers insights on the application of the C2C concept in the built environment reporting on the limitation and means of improvement.
Keywords: Cradle to Cradle, building design, energy, materials, biological and technical cycle, assessment

INTRODUCTION

The Brundtland Report and the Intergovernmental Panel on Climate Change (IPCC) Report agreed to describe the current environmental imbalance as follows: "the human demand on the planet is exceeding the planet's regenerative capacity" [1 & 2]. In order to prevent this imbalance, current generations have been taken to challenge the resources conservation and management. Many bodies, institutions, companies and industries have already begun to change their way of thinking, living, producing and consuming. Some of them try to use only products from "ecological" or "sustainable" producers and recycle all they can; others try to diminish their environmental footprint in reducing their consumption of non-renewable products. According to the Cradle to Cradle (C2C) paradigm [3, 4], almost all of these efforts have one common purpose; they try to be efficiently "less bad". On the opposite, the general idea of the C2C approach is to design products, in this case buildings, in order to have a positive impact on the planet, instead of trying to go beyond the zero environmental impact concept.

The overall aim of this research is to apply the C2C paradigm within the built environment. The objective is to design and assess a building prototype following the C2C principles. The design prototype has a specific focus mainly to close the energy and material cycle in buildings while maintaining comfort. Other C2C criteria like water, material health and social fairness are excluded from the study and might be considered in future work. The specific research question relates to the investigation of the ability to achieve a C2C house in Switzerland using local Swiss materials and construction techniques. To answer this question, a building prototype will be designed and its performance will be quantified regarding its operational and embodied energy. The significance of this study is mainly based on implementing and contextualising the C2C paradigm and methodology in Switzerland. The paper audience is architects, building designers and researchers working in the field of sustainable building construction. The paper findings can support the decision making for building community and highlight important facts (potential/challenges) on possibilities of applying C2C paradigm in Swiss built environment.

This paper is organized into five sections. The first section introduces the objectives and context. The second section explains the essential concepts of the C2C design paradigm and includes a brief literature review on related analysis and case studies. The research terminology, methodology and prototype boundary conditions are presented in Section 3. The analysis of the energy performance and building materials biological and technical cycle, are presented in Section 4. The final section discusses the research findings and limitations, along with the implications for the design practice community and future research.

C2C DEFINTION AND PRINCIPLES

The contemporary building construction industry is operating within a cradle-to-grave model. This means builders are buying building materials, occupants used them and then they end up in landfills or incinerators. In the last twenty years, most building industries adopted environmental approaches or eco-efficiency approaches by producing less bad products through the reduction of their negative environmental impact. Within the C2C paradigm, the eco-efficiency approach is strongly criticised because it leads to being less bad instead of being better [3]. Eco-efficiency is mainly promoting reduction and recycling, which leads to materials downcycling while maintaining the same typical cradle to grave model. So eco-efficiency is only a short term strategy for serious, accelerating environmental problems. For example, buildings are commonly designed mostly for its operational use, and not its potential next use after it is deconstructed. This means that the building elements cannot be considered as optimally designed from the start.

The overarching goal of C2C paradigm is to create a good design, which raises eco-effectiveness. If we look at nature, we can get a better understanding of the C2C paradigm. For example, a tree provides food for animals, insects and enriches the ecosystem by sequestering carbon and producing oxygen. At the end of its life, it will return to the soil by decomposition and a new tree can grow again. So eco-effectiveness in buildings design is inspired by nature. For a good design, considering and mimicking the whole system is essential.

For this study, we followed three major C2C principles to design and later assess our prototype [3]. The first concept is: “Waste Equals Food”, similarly to what happens in nature: all what could be seen as “waste” is actually a nutrient used again in a cycle. The second principle is that these nutrients are coming from two metabolisms: the biological metabolism and the technical metabolism. The first one comes from the natural cycle and the second from the industrial cycles. Every product has to be iterating in its own cycle, which means that products are either decomposable or infinitely recyclable. Mixing materials between both metabolisms must be avoided in order to increase the quality of the materials and to make their retrieval easier. In fact, designers have to learn how to imitate nature’s nutrients flow and metabolism to avoid the negative environmental impact of their buildings. The third principle is about celebrating diversity, this means considering how building components are made and also how they will be used over time in the biosphere. Using local materials, building according to local conditions and diversifying the energy production are very important criteria. The three C2C principles could be summed up, under one sentence: “Imagine a building like a tree, a city like a forest”.

LITERATURE REVIEW: STATE OF THE ART

The major publications related to the C2C concept focusses on the C2C theory and principles and guidelines for C2C product development [3-16]. The C2C Built Environment Manual, that set guidelines for the Danish building community [17], completes these by an example of a C2C building code.

The C2C paradigm can be considered as a paradigm dictated by theories and principles for C2C products. Based on this survey of the C2C paradigm it shows that very little information is however available in literature regarding buildings. According to the C2C Products Innovation Institute [16] it is not possible to get a building certified as C2C, but products can get certified. This means that we had to set our individual assessment method in line with guidelines found in the literature [11, 17]. The certification method proposed suits only to products [20] and not to assemblies like buildings. Therefore, for this study, we assessed the prototype performance without being able to compare it to other C2C building benchmarks.

Next, a case studies review of projects was conducted to learn from existing implementation projects that adapted the C2C concept. Two main projects were studied the "Knik naar Zon” project [18] and the “2020 Park” [19] in Venlo. However, both projects are still under implementation and they are adapted to the Dutch context as no example of Swiss buildings which totally follow the C2C paradigm could be found; though many are already going in a similar direction. This requires establishing new definitions and metrics to estimate to which extend a building is C2C, which will be discussed below.

METHODOLOGY

The research methodology is based on a cyclic design process, including several iterations. The building is a prototype for a residential house in Switzerland. In order to shorten the materials list, we excluded furniture and home appliances in the material inventory but their electricity consumption is taken into account.

The design iterations are informed through a rigorous selection process and a dynamic detailed building performance simulation for renewable, operational and embodied energy. Based on the literature review two basic manuscripts were used to develop a new iterative design and assessment process: The Hannover Principles [12] and Reinventing the World [19] by Mc Donough and Braungart. This strategy presents a way to design C2C products for businesses and to realise the transition from eco-efficiency to eco-effectiveness on the level of product design. By C2C products we mean construction products that are at least 95% identified down to the parts-per-million level and evaluated for safety to human and environmental health.

The following paragraphs describe first of all the selection process and secondly the performance assessment process the in detail as shows in Figure 1. The selection process of materials is based on four major steps towards eco-effectiveness. While moving between the four steps the design prototype is developed in a cyclic approach taking feedback from each step regarding the building components and material choice.

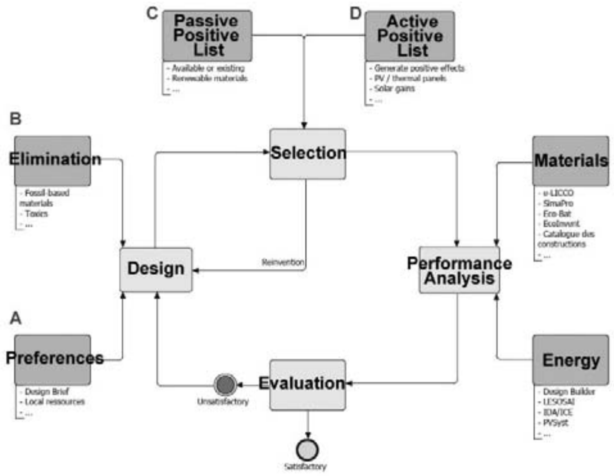

Figure 1: Developed iterative design and assessment process of a Cradle to Cradle building prototype

The first step (A) is called Personal Preferences. This step allows defining the project brief and functions and the potential local materials and building products through an inventory. The selection criteria for material regarding their environmental impact at this step are not strict allowing the choice of potential local materials. Materials should be classified as either originating from biological or technical cycle, with the associated metric being the volume percentage, expressed in [%Vol.]. Also at this step we defined the prototype as a plus energy i.e. building producing more energy during its operational use than what it consumes plus what its embodied energy accounts to. The metric which refers to it is the embodied Energy expressed in [kWh]. The second step (B) is a filtration step, looking at replacing dangerous substances (health) and nature contaminating products by other substances that are 'better' i.e healthier for the occupants. The third step (C) is aiming to create a passive positive list, a systematic classification of the products according to their dangerousness (regarding the danger for the health of people) and their usability. The active positive list is the fourth step (D), where the previous passive positive list is optimised to clearly separate the biological and technical nutrients.

Once this selection process is achieved the second loop starts, which is the performance assessment. To achieve both, material and energy assessment, a quantitative list of all materials was created and energy needs were defined. The energy performance assessment of the prototype was done using DesignBuilder [21] and PVSyst [22] software. The simulation model was calibrated through a comparison with similar high performance residential buildings [23]. The material assessment was made through a life cycle analysis, using SimaPro [24] using ecoinvent [25] database.

RESULTS

A detailed study report [26] was created including the study outcomes of the prototype design. In the following paragraphs the most significant results are summarised.

Prototype Design

The prototype design illustrated in Figure 2, consists of a detached single-family house with four occupants. The building has no crawl space or any urban surroundings to allow maximum solar access. The design complies with the Swiss building energy label Minergie-P and SIA-380 standard [23 & 27]. Preference was given for energy efficient technologies, local fabricated products and onsite renewable energy generation.

Figure 2: Cross section, Ground floor and First floor.

Materials Selection

During the first design iteration and based on the personal preferences step (A), a priority is given for C2C components with a clear nutrients cycle documentation. Because at that stage it was not possible to find sufficient materials and components that comply with the C2C criteria. Therefore we decided that the 'best' market available material or component should be selected at each step. This allowed us to move to the elimination of undesirable substances step (B), where we decided that bad products and processes could be used only if no other better equivalent product were available. Undesirable products typically relate to building components which imply a large consumption of fossil-based resources and those which are known to contain toxic substances. The use of products that are coming from very far and transported on thousands of kilometres is undesirable too.

The passive positive list (C) was created by emphasizing renewable materials like wood and avoiding fossil fuel based products, especially insulation materials. The active positive list (D) included Photovotaic (PV) and thermal panels.

The envelope construction is a wooden framework. This choice allowed reducing the quantity of concrete and the embodied energy. The only disadvantage of the wooden structure is the low thermal mass which affected the energy consumption. However, wood was chosen due to its abundance as renewable material in Switzerland [25]. The material for thermal insulation was difficult to choose since it was difficult to find reliable information on insulation materials. Finally cellulose insulation, locally produced, was selected. The mechanical ventilation system is a double-flux system with heat recovery feature. The heating system is a heat pump coupled to the hot water tank to benefit from the heat surplus provided by the thermal panels. The PV panels provide electricity needed for the heat pump and the building is connected to the electric grid.

Operational Energy

The performance simulation result is illustrated in Figure 3. The figure shows that 47% of the annual energy needs can be met passively from the solar gains. This is due to the large south facade WWR (50%). A monthly heat gains analysis breakdown is shown in Figure 4. During summer the heating gains are too high and therefore shading devices were integrated in the final prototype.

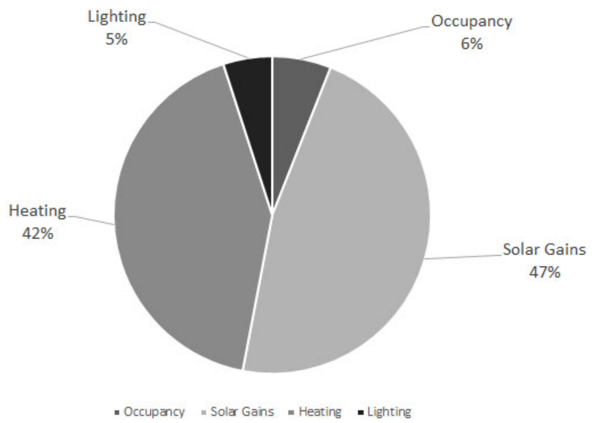

Figure 3: Heating gain distribution

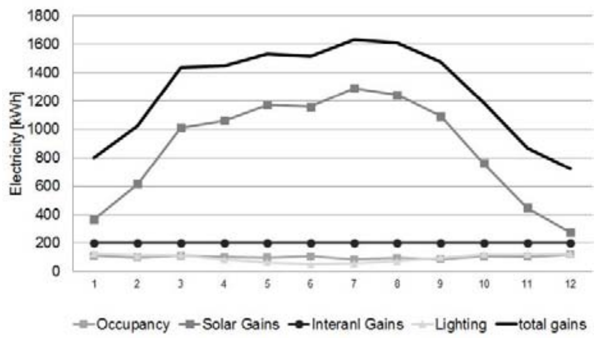

Figure 4: Monthly heat gain

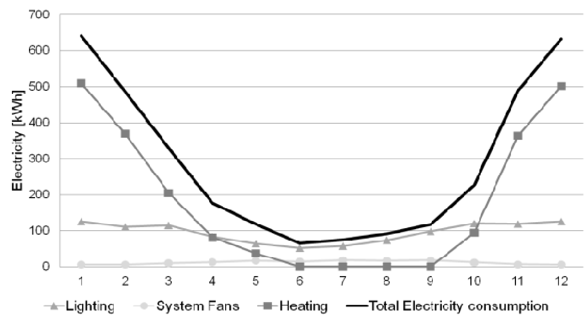

Figure 5: Monthly electricity consumption.

Thermal comfort was evaluated during the summer season and building complied with the SIA 380 requirements for indoor temperature. The monthly electricity consumption of the prototype was estimated to be 3345 kWh/year based on building performance simulations (Figure 5). Taking advantage of the full roof area for PV installation the total onsite generated electricity is 8825 kWh/year.

Embodied Energy and the Energy Balance

The aim of energy balance assessment was to define the ability to exceed the operational and embodied energy requirements through onsite renewable generation.

Figure 6 shows that during the 30 year operational life of the prototype, 71% of the total required energy correspond to embodied energy while the remaining 29% correspond to the operational energy. This ratio between operative and embodied energy is mainly caused by large volumes of thermal insulation. In the same figure, it can also be seen that onsite energy production covers 74% of the embodied and operational energy for the prototype. This means that from a C2C perspective this prototype cannot become a positive C2C energy house.

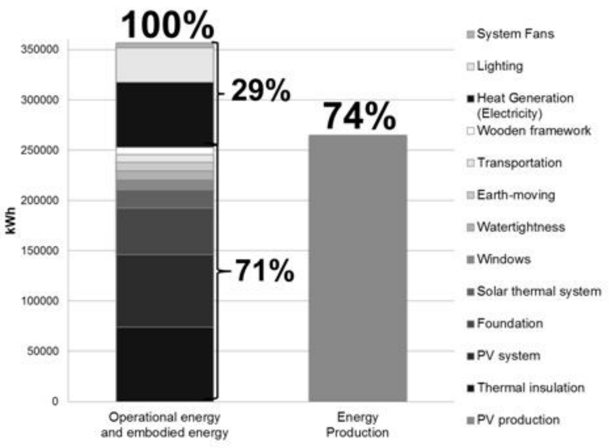

Figure 6: Operating and Embodied energy.

Biological and Technological Cycles Analysis

The results of the Biological and Technological Cycles analysis are shown in Figure 7. The analysis was done to indicate the total non-renewable embodied energy of the building components for a period of 30 years.

A final material assessment was conducted to examine all materials used in the final prototype and to define the percentage of C2C materials. The assessment results indicated that only 8.4% of the whole building material inventory could be classified as C2C, this corresponds mainly to the wooden structure. Other materials including the cellulose insulation could hardly be decomposed in the biological cycle or up cycled in the technological cycle.

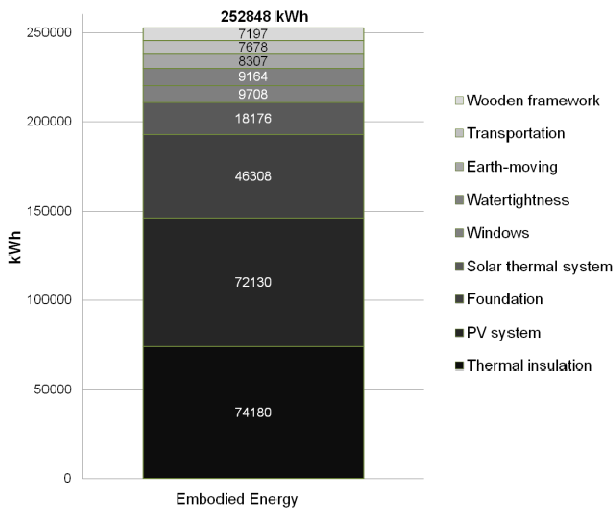

Figure 7: Total non-renewable energy.

DISCUSSION

The study showed that the building prototype designed in this work can be 74% C2C from an energy balance point of view. According to the given definition, only 8% of the building prototype is C2C from a material balance point of view. The C2C oriented approach used here shows the difficulty of finding suitable materials that will not end up in incinerators or landfills. Confronting our existing design practice with the C2C paradigm and principles is very enlightening. The research findings show that energy problems might be solved on the short term, but materials are still a challenge. With the current tendency of insulating new constructions with huge amounts of insulation materials, we are shifting the environmental problem from the now to the long term future. This means that future generations will be confronted with huge amounts of waste materials that could not be recycled or decomposed in the techno sphere or biosphere.

On the other hand, it is not realistic to build a C2C building today in Switzerland. There are no available components and solutions that can cater to the market and construction industry. According to the study findings, only 8.4% of the whole material volume used in this prototype could be C2C certified. We tried to find materials that can be listed on the Positive list (C& D). This means that industry is far behind this concept. We tried to achieve the C2C prototype using different architectural design strategies but this was not enough. The major handicap was to find materials that are designed to become a part of a building solution. Moreover, there is a need for metrics, design methodology and benchmark studies. This will allow to compare our results and validate the proposed methodology shown in Figure 1.

Finally this study remains theoretical with many assumptions that need to be validated. The calculation was based on 30 year duration; even the methodology and metrics were specifically created to match the building design process. There are other limitations of the study like the exclusion of water, health and cost. Future work will focus on a more detailed products review looking at different alternatives for insulation materials and materials assembly, an issue that was not raised in the paper. We consider the construction techniques as another important challenge for C2C buildings since we are trying to avoid amalgamating hybrid composite and components that could be easily dismantled, disassembled and speared.

CONCLUSION

This study showed the difficulty to implement a C2C building in Switzerland. The study showed that the building prototype designed in this work can be 74% C2C from an energy balance point of view. If we could add an additional 33m^2 of PV, we could reach 100%. The additional PV surface will have to compensate the 26% of embodied energy and operational energy and should be mounted beyond the building roof. Another important result is that according to the given definition, only 8% of the building prototype is C2C from a material balance point of view. In order to increase this percentage, C2C products, materials and assemblies have to be developed and provided in the market.

The present study shifts the focus from energy to materials. Future work should focus on possible assemblies and solutions for C2C construction materials coupled to a clear C2C design methodology, metrics and analysis protocol. An extension of this study can be in the form of parametric analysis of insulation materials looking at long term environmental impact.

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