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Residential area building project's carbon emissions with the hybrid LCA approach

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Abstract—**Buildings account for roughly one third of all green house gas emissions globally. Identifying the sources of these emissions and understanding their relations to the construction phase is essential in diminishing the emissions. The study evaluates the CO2-emissions caused by a residential construction project in Finland. The research method is modified tiered hybrid life cycle assessment. An input-output method EIO-LCA forms the basis of the tool which is enhanced with current and local process data. The results of the study reveal that the sources of the CO2-emissions of residential area construction projects are divided into numerous categories. Thus diminishing the emissions is difficult as there are no dominant materials in terms of CO2-emissions. The results of the study provide an estimate of the CO2-emissions of the case project and also the relative shares of the most important construction materials and functions. The results of the study may be applied to the evaluations of similar construction projects. The research method may also be used in future research as well as in further development of hybrid LCA-methods.**

Keywords-component; life cycle assesment (LCA), residential area constructions, EIO-LCA, hybrid LCA

I. Introduction

According to recent research, climate change is threatening mankind's well-being in the future [1]. Carbon dioxide (CO2) is the most significant greenhouse gas caused by human. All kinds of burning processes cause CO2-emissions and it is considered as the mankind's most significant waste product. Even though CO2's share of the atmosphere is still relatively low, its concentration is growing as the decay is slow. Due to this, attention should be paid to the time perspective in addition to the volumes of greenhouse gas emissions (GHG's). Thus, understanding the problem and the underlying causes together with prevention and minimization of the effects belong to the most significant global challenges in the near future [3].

Carbon footprint has been established as the common way to examine GHG emissions related to certain processes or goods. Determination of the carbon footprint is based on the life cycle assessment where climate change is the only effect group [4]. Previous research reveals that most of the CO2-emissions caused by people are heavily connected to the residential energy consumption, construction, travelling-related infrastructure and establishment issues [5, 6, 7]. Finding out quantities and sources of these CO2-emissions is essential in order to reduce the carbon emissions and slow down climate change.

Life cycle assessment (LCA) is a method used for measuring the comprehensive environmental effects of objects and actions. Besides the direct environmental effects, LCA also measures the indirect effects beginning at the acquisition of raw materials and ending at the disposal of the product [8, 18]. In previous research, LCA has been the tool for measuring and comparing the environmental effects of different material and product options, building types, energy options etc. [8, 9, 10, 11]. In addition, LCA has quite recently been used more and more to study the activities in society that cause CO2-emissions and their relative shares [4, 7, 12]. Some of the previous research has focused on comparing the different LCA-methods and their applicability in various conditions [13, 14, 15].

While the LCA method has previously been utilized in construction research, large gaps in the knowledge related to the emissions of construction remain. Several studies concerning life cycle wide environmental loads of the specific construction materials exist [16, 17]. In addition, the GHG emissions from construction of different building types have been studied. However, few studies with life cycle perspective on environmental effects of whole residential areas exist. Besides the construction of residential buildings, the constructions of communal buildings and infrastructure also have significant impact on the carbon footprint of a residential area.

The paper studies the life cycle wide environmental effects of Nupurinkartano residential area construction project in southern Finland with two different LCA-methods. The purpose of the paper is to provide an estimate for the CO2-emissions caused by a residential area construction project, and to test the applicability of LCA method in the selected framework. In addition, the results of the paper provide a possible comparison of different LCA-methods in modeling emissions of construction projects. The hybrid LCA-tool built for the study can also be used in forthcoming research as well as a basis for future hybrid LCA-tools.

II. Research Design

The research method used in the case study is life cycle assessment (LCA). The two LCA applications used in the study were input-output life cycle assessment (EIO-LCA) and hybrid life cycle assessment (hybrid LCA).

The process LCA is the traditional method used in life cycle assessments [8, 18, 19]. Process LCA is a potential life cycle assessment tool for getting the most accurate results, especially on homogenous and distinctive cases as construction projects [15]. The reason for accurate modeling results lies in the initial information that is usually locally and temporarily correct. The boundary definition of the process LCA assessments sets a significant challenge in conducting accurate life cycle wide modeling [18]. The process chain has to be cut in some point and the processes that are left outside the assessment might have relevant impact on the results [18]. Process LCA is also a time consuming and an expensive way of conducting life cycle research [15]. The initial process data used in the modeling may also be challenging to obtain and the programs used in the modeling process are usually expensive [15].

The second method, input-output life cycle assessment IO-LCA connects the monetary costs of the products or actions with environmental impacts through output matrices for certain input that utilize industry average data [13]. The IO-LCA-method was invented by the Nobel Prize winner Wassily Leonthief in the 1970s. EIO-LCA has several advantages compared to process-LCA-method. IO-LCA-tool uses national economy wide national input-output matrices to calculate direct and indirect environmental impacts for each monetary investment. Consequently this characteristic of the method nullifies the truncation problem of the process LCA. Conducting an IO-LCA is also time efficient compared to a process-LCA [8]. However, IO-LCA method also carries a few disadvantages. There are only a couple of national models available which in addition are several years old. IO-LCA also uses an aggregated national sector for each object or assessment and characteristics of the specific processes cannot be taken into consideration. Consequently, the IO-LCA modeling tool is not suitable for comparing different objects inside the sectors.

Hybrid LCA models are designed to combine the most suitable characteristics of both IO-LCA and process LCA models. They allow both an avoidance of the truncation error of process LCAs and a reduction of aggregation error inherent in IO-LCAs [18]. There are a couple of different applications of hybrid LCA method, which are discussed in detail in the paper of Bilec et al. (2006).

IO-LCA based application of tiered hybrid LCA is used in the study. The application of IO-LCA method used is the economic IO-LCA (EIO-LCA) which is provided by the Carnegie-Mellon University [2]. A free-access version of this modeling tool is available at the Carnegie-Mellon University's web page. The model is based on US Industry, the reference model of the most recent version being from the year 2002.

Hybrid LCA method used in the study is the modified tiered hybrid LCA. It is significantly based on the results of the initial IO-LCA-modeling. The hybrid model consists of EIO-LCA basis and the most important materials or functions based on the CO2-emissions are modeled by means of adding local and current process data into the modeling tool.

The case study of the paper is Nupurinkartano residential area that will be built in Espoo, a city located in southern Finland. The development of the area started in 2004 by conducting a planning and various reporting. Nupurinkartano residential area is intended to accommodate 550 to 600 people. The residential area is planned to consist of 219 houses that will for the most part be terraced houses, semi-detached houses and detached houses. The sizes of the houses will be 70 to 160 m^2. The residential area consists of approximately 54 hectares. Total permitted building volume for the area is about 35400 m^2.

There were two phases in the study. The first phase was the EIO-LCA modeling of the case project. The initial data of the project were received by e-mail from the developer company. The data included total costs of the construction project sorted by the materials and the functions. Ten most important materials were specified as were services' and energy's part of the total costs. The total construction costs of the buildings of Nupurinkartano are 69.39 million euro and the total costs of the infrastructure are 6.93 million euro according to the cost data. Choosing the most appropriate sector for each material or function is an essential phase in the EIO-LCA modeling process. The EIO-LCA tool then provides the life cycle wide CO2-emissions for each sector according to the invested monetary value. Cost sorting, selected EIO-LCA sectors, monetary values and CO2-emissions are presented in table 1. Table 2 presents the process data that will replace the correspondent EIO-LCA sectors in the hybrid LCA modeling part of the study.

Table 1

Table 2

The second phase of the study was a hybrid LCA modeling of the construction project. EIO-LCA modeling forms the basis of the hybrid model and the EIO-LCA foundation is enhanced with a process data for the most significant materials and functions. According to the EIO-LCA modeling, the most significant single materials and functions of the project were energy, concrete and steel not only because they cause most CO2-emissions but also have the highest CO2-intensity of all materials and functions. Thus, they were chosen to be modeled with a more accurate method, the process-LCA.

The emissions for the energy used in the construction project were modeled using the local power company Fortum's reports of the year 2009. The study assumes that energy used at the construction site is produced locally. Suomenoja power plant in Espoo generates electricity and district heat using coal and natural gas as a fuel. Heat is produced as electricity's by-product. Joint production of electricity and heat covers 80 percent of Espoo's need for district heat [20]. According to the developer company the total need of the electricity for the construction of buildings is about 11765 MWh. Suomenoja power plant produced 2714 GWh of electricity and heat in the year 2009 [21]. The total CO2-emissions of Suomenoja power plant were 817 000 tons [22]. Thus the CO2-intensity of the power generation is approximately 301 g/kWh. Accordingly the total CO2-emissions caused by the energy production process are 3542 tons.

These are the direct CO_2-emissions caused by the energy production. In order to include also the indirect emissions, the higher order tiers of the supply and production chain were added from EIO-LCA sector "Power generation and supply". The total indirect CO_2-emissions for the electricity production were 653 tons. Thus the total life cycle wide CO_2-emissions caused by the electricity are 4195 tons.

The initial EIO-LCA modeling of the construction project revealed that concrete and steel are the most relevant construction materials regarding CO_2-emissions. Process information of concrete and steel were acquired using the environmental reports of Rakennustietosäätiö RTS [17]. Process information includes the life cycle emissions of the products beginning from the acquirement of raw materials and ending at the gates of the manufacturing factory. Concrete and steel products were divided into subcategories by the developing company and every subcategory was paired up with an appropriate environmental report. The environmental reports of concrete and steel products are based on the products of typical Finnish manufacturers. The amounts of steel in wall elements and hollow-core slabs were estimated according to Lounamaa (2010) and the amount was reduced from the concrete steels in order to avoid double counting. Initial data of concrete and steel materials and their respective CO_2-emissions are presented in table 2.

III. RESULTS

According to the utilized tiered hybrid LCA model, the CO_2-emissions of the Nupurinkartano construction project are 60542 tons. With the initial EIO-LCA model (table 1), the total CO_2-emissions of the Nupurinkartano construction project were 70800 tons. In the hybrid LCA, the dominant sectors in carbon emissions are energy production with 4195 tons, concrete with 6121 tons, steel with 3613 tons and infrastructure with 5169 tons. The higher order tiers create together 41444 tons of CO_2-emissions.

The infrastructure's share of the emissions is about seven percent in the EIO-LCA modeling and nine percent in the hybrid LCA-modeling. Thus buildings' share is 93 percent in the EIO-LCA and 91 percent in the hybrid LCA part of the study.

The same sectors dominate the results of both modeling tools although the distribution is wide. The most dominant single material or product in the EIO-LCA modeling is energy whose share of the total CO_2-emissions of the buildings' construction is approximately 17 percent. Energy's share of the buildings' hybrid LCA emissions is approximately eight percent. Concrete's share of the buildings' EIO-LCA modeling is approximately 11 percent with both EIO-LCA and hybrid LCA models. Corresponding figures for steel are approximately ten percent with EIO-LCA and seven percent with hybrid LCA approach. Figure 1 presents the costs of buildings and their respective emissions with both analysis tools where available so that relations between costs and CO_2-emissions may be observed.

Figure 1

IV. DISCUSSION

The purpose of this study was to estimate the CO_2-emissions of a residential construction project in Finland. The research methods used in the study were input-output-LCA based EIO-LCA and modified tiered hybrid LCA. The case project of the study is Nupurinkartano residential area in Espoo, Finland. The residential area is planned to accommodate 550 to 600 inhabitants.

The total CO_2-emissions of the residential construction project are 70800 tons with EIO-LCA and 60542 tons with hybrid LCA method. Thus hybrid LCA method comes out with approximately 14 percent lower CO_2-emissions compared to EIO-LCA. The main reason for the difference is the local energy provider's carbon profile, which is better when compared to the correspondent EIO-LCA sector. Emissions of the building materials are caused by numerous sources and most of them are not very significant on their own. Most important single sources of CO_2-emissions were energy (eight percent), concrete (11 percent) and steel (seven percent).

Identified uncertainties of the IO-LCA method include temporal bias plus accuracy and aggregation problems [18]. The modified tiered hybrid LCA method used in the study was created in order to obtain more accurate results compared to the initial EIO-LCA modeling. EIO-LCA, which formed a foundation of the hybrid LCA model, is the most disaggregated IO-LCA method because it has most sectors available [2]. The most input-output tables also assume that imported products are produced domestically [18]. In most scenarios CO_2-intensity of foreign production does not correspond to the domestic production and resulting emissions might be biased. Suh et al. (2004) discusses the problem in detail. In this study the bias might exist in the EIO-LCA, but in the hybrid model the coverage of the process data diminishes the bias significantly.

EIO-LCA foundation of the hybrid LCA model provides a way to avoid the truncation problem and process-LCA data improves the accuracy of the model. The results of hybrid LCA modeling were approximately 14 percent lower than the EIO-LCA results. However the hybrid LCA model has a significant EIO-LCA foundation. The CO_2-emissions of concrete, steel and energy acquired by the process modeling were 42 percent lower than their respective EIO-LCA counterparts. The model might be improved by replacing more significant EIO-LCA sectors with process data.

The purchasing power parity (PPP) tables were used to avoid biases caused by temporal factors such as inflation and currency rate differences between present Finnish economy and US industry 2002 model. The purchasing power parity 2005 table is provided by The World Bank. Weber et al. (2007) has used the similar correction in his study. The PPP USA – Finland coefficient is 0.98 [23].

Comparing the EIO-LCA sector results with the local and actual process data is a suitable way to analyze EIO-LCA tool's suitability as a modeling tool. CO_2-emissions of materials and electricity obtained with process data were lower than EIO-LCA results in all cases. EIO-LCA CO_2-emissions of concrete products were 13 percent higher, steel products 74 percent higher and electricity 262 percent higher than the process data results. One of the reasons behind the big differences in results lies in the composition of EIO-LCA sectors that are different between the US and Finnish economies.

The EIO-LCA modeling represents a major part also in the results of hybrid LCA modeling by the share of 77 percent. The selection of EIO-LCA sectors for the most essential functions and materials has significant consequences on the results. The processing level of certain sectors is essential when making decisions on the sectors. Concrete products may be modeled for example with two sectors. "Cement manufacturing" has a low processing level and is very CO2-intensive compared to "concrete pipe, brick, and block manufacturing" sector which was used in the study. "Cement manufacturing" sector results six times higher CO2-emissions than "concrete pipe, brick and block manufacturing" sector. However, concrete materials used in the construction projects such as Nupurinkartano usually have a higher level of processing than "cement manufacturing" sector has.

There are also two possible EIO-LCA sectors for steel materials. "Iron, steel pipe and tube manufacturing from purchased steel" is a sector that was included in the study. An alternative is "iron and steel mills" which has a lower processing level and thus a higher CO2-intensity. Using the "iron and steel mills" in the EIO-LCA modeling would have almost doubled the CO2-emissions caused by steel materials.

Although EIO-LCA tool only has one sector for power generation the hybrid model is exposed to particular uncertainties that are connected to electricity modeling. The method used in the study is based on the assumption that the electricity used in the construction project is produced locally. The local power company Fortum's Suomenoja power plant has a CO2-intensity of 301 g/kWh which is moderately high when compared to the alternatives. Fortum's average CO2-intensity of the electricity production in the year 2009 was 134 g/kWh and the average CO2-intensity of Fortum's power plants in the EU region was 41 g/kWh in the year 2009 [22]. The CO2-emissions of the construction project would have been only one seventh of the current results if Fortum's average CO2-emissions in the EU region were used.

The total amount of CO2-emissions (60542 tons) is equal to the CO2-footprints of 4800 people living in Helsinki metropolitan area. The amount of CO2-emissions per one inhabitant in Nupurinkartano residential area is approximately 100 tons. This may be compared to the average carbon footprint of a citizen living in Helsinki metropolitan area which is 13.2 tons [3]. Constructions of new residential areas seem to cause large emissions in a short period of time. The time-oriented perspective on emissions of constructions is a relevant subject for future research.

More similar construction projects should be modeled with the same research method in order to validate it. Modeling the past construction projects the CO2-emissions of which are known could also clear up the error margins of the research method.

According to previous research construction phase's share of the building's life cycle CO2 emissions is only 10 percent [5]. Thus CO2 savings acquired in the construction phase do not have a major role in lowering the life cycle CO2-emissions of the buildings. On the contrary, if actions made in the construction phase could lower the CO2-emissions of the use phase, they should generally be adapted even if the CO2-emissions of the construction phase increased.

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TABLE I. CATEGORIES, COSTS AND EMISSIONS OF CONSTRUCTION PROJECT. BOLDED SECTORS WERE REPLACED WITH PROCESS DATA

Infrastructure

Material or function	EIO-LCA sector	M€	Total t CO_2e
Other construction components	Nonresidential maintenance and repair	3,66	2234
Mixed used streets' construction components	Museums, historical sites, zoos and parks	0,32	154
Construction components of water supply and sewage	Water, sewage and other systems	1,17	2048
Contractor's costs	Residential permanent site single- and multi-family structures	0,89	577
Designing	Architectural and engireening services	0,42	76
Investor's and owner's tasks	Management of companies and enterprises	0,47	79
Total		**6,93**	**5169**

Buildings

Material or function	EIO-LCA sector	M€	Total t CO_2e
Timber	Sawmills and Wood Preservation	4,96	3577
Concrete	**Concrete pipe, brick and block manufacturing**	**3,68**	**6919**
Steel	**Iron, steel pipe and tube manufacturing from purchased steel**	**3,16**	**6292**
HEVAC-material	Air conditioning, refrigeration, and warm air heating equipment	2,72	1548
Brickwork (bricks + plaster)	Brick and Structural Clay Tile Manufacturing	2,22	4371
Electric material	Miscellaneous electrical equipment manufacturing	1,92	714
Windows and doors	Wood Window and Door Manufacturing	1,88	1098
Energy	**Power generation and supply**	**1,2**	**10976**
Furniture	Nonupholstered Wood Household Furniture Manufacturing	0,97	466
Water insulation	Paint and Coating Manufacturing	0,71	748
Domestic appliance	Household Refrigerator and Home Freezer Manufacturing	0,59	451
Plastic pipes and basins	Plastics Pipe and Pipe Fitting Manufacturing	0,51	702
Heat insulation	Industrial Process Furnace and Oven Manufacturing	0,47	232
Subcontractors	Other nonresidential structures	26,40	15876
Others	Residential permanent site single- and multi-family structures	18,00	11662
Total		**69,39**	**65631**

TABLE II. PROCESS DATA THAT REPLACED CORRESPONDENT EIO-LCA SECTORS IN HYBRID LCA MODELING

Concrete products:	**Volume (m^3)**	**Density (kg / m^3)**	**Mass (kg)**	**CO_2 (g / kg)**	**CO_2 (t)**
Wall elements	6 262,3	2 400,0	15 029 520,0	250	3 757,4
Hollow-core slabs	2 419,1	1 358,5	3 286 324,5	140	460,1
Beams, pillars ja prestressed concrete	81,0	2 520,0	204 120,0	220	44,9
Bars	877,5	400,0	351 000,0	265	93,0
Ready-mixed concrete	6 427,0	2 400,0	15 424 800,0	110	1 696,7
Patio tiles	257,6	2 239,0	576 766,4	120	69,2
Total	**16 324,5**		**34 872 530,9**		**6 121,3**

Steel products:	**Mass (kg)**	**CO_2 (g / kg)**	**CO2 (t)**
Concrete steels (element steels excluded)	492 774,6	6 400	3 153,8
Plates and section wires	347 652,4	1 150	399,8
Steel pipe beams, pillars and profiles	55 435,5	1 070	59,3
Total	**895 862,5**		**3 612,9**

Energy:	**EIO-LCA sector**	**M€**	**Amount (MWh)**	**CO_2 (g / kWh)**	**CO_2 (t)**
Suomenoja Power Plant			11765	301,06	3542
Indirect emissions of electricity production	Power generation and supply	1,2			653
Total					**4195**

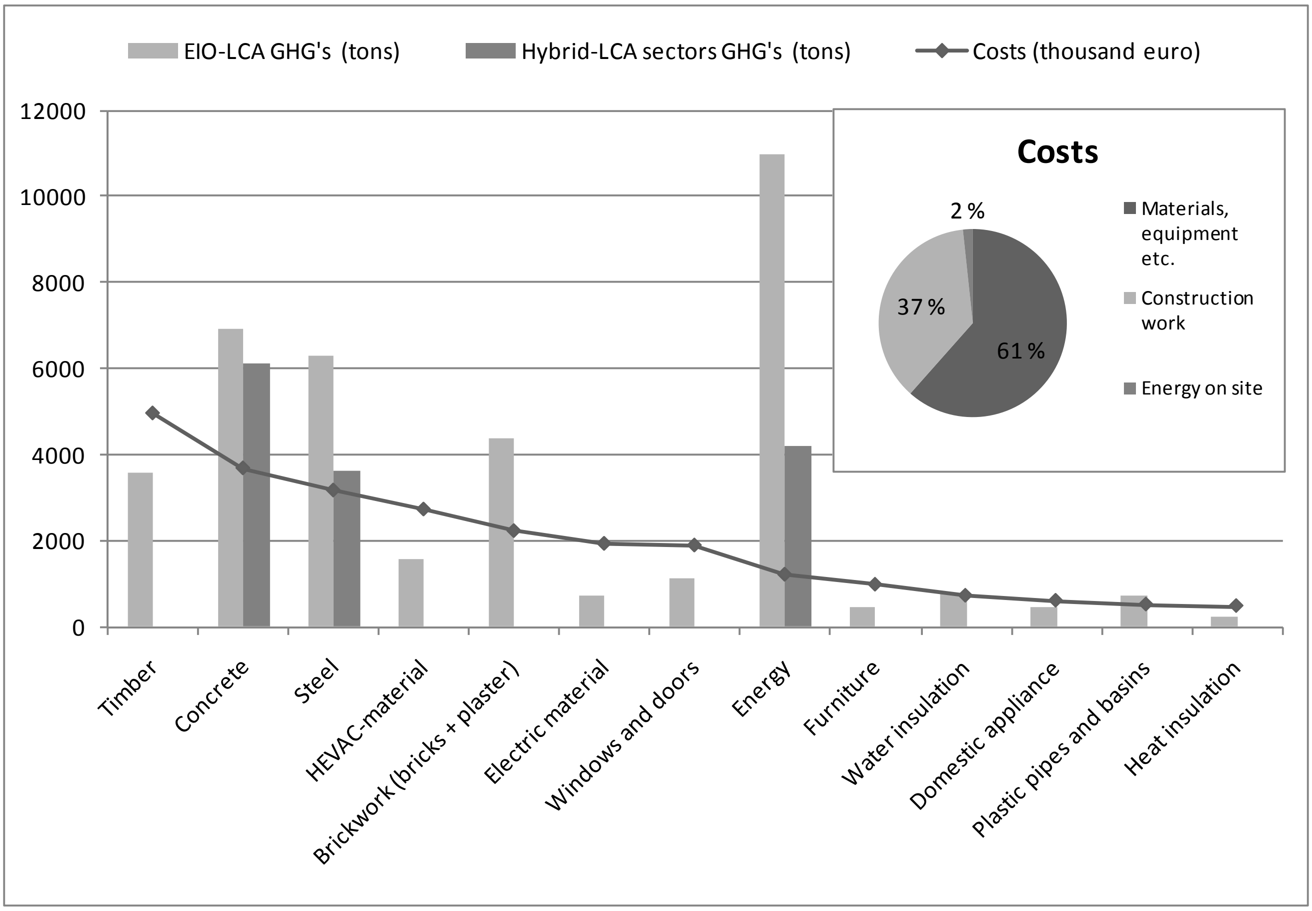

Figure 1. Structure of the project's costs and the emissions of the most important buildings, materials and energy